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A PROTOTYPE SYSTEM FOR THE BALANCING OF MASS AND ENERGY IN A POTASH CIRCUIT

DECEMBER, 1984

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A PROTOTYPE SYSTEM FOR THE BALANCING OF MASS AND ENERGY IN A POTASH CIRCUIT

FINAL REPORT

BY

KILBORN LTD

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ABSTRACT

This report presents the results of a study on the development of a practical tool for the analysis of mass-flow and energy in a potash circuit. The work has culminated in the development of a prototype microprocessor system capable of solving mass-energy balances and is demonstrated in the worst case situation of a potash crystallizer for industrial circuits of major complexity. Contained within the report are specifications for hardware and software components that can be used to operate the application programs of the study. In this sense, the report is a user guide for researchers and plant designers.

The general subject of process control is addressed from the standpoint of energy management along with some of the technical issues that retard progress in potash technology.

The report discusses process control instrumentation and provides the specifications for an economical general purpose instrument for on-line mass-energy calculations to be used for process optimization.

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BACKGROUND SUMMARY AND RECOMMENDATIONS

In 1983 Kilborn was awarded a DSS contract (OSQ.23440-2-9172) to study the "Optimum Control and Conservation of Energy in the Crystallization, Drying and Cooling of Potash". Foremost among the conclusions of the study was the recognition of the importance of energy management and control. The study highlighted the need to solve the numerical analytical problem of balancing mass and energy and developed a procedure that was demonstrated on a large computer.

The procedure was confined to the case where important constituents such as $MgCl_2$ and insoluble materials could be neglected. The former assumption is completely invalid for the entire producing tract known as the Esterhazy member of the Prairie Evaporite and the latter is a poor assumption for most potash circuits, including the front end of a crystallizer circuit.

The procedure was inefficient and uneconomical because it could only be completed on a large mainframe computer. Moreover, it has since been learned that the procedure was very far from completion when the calculations had to be terminated due to the exhaustion of the computer time budget.

However, the study revealed the importance of the mass-energy procedure and showed that the balancing problem was generally regarded as unsolvable even when all known procedural simplifications were included.

In the Saskatchewan potash industry the desire to obtain routine practical solutions, to the mass energy balancing procedure, is augmented by a desire to integrate the procedure with on-line measurement and process control systems. These goals were clarified at the "Potash 83" International Conference in Saskatoon(7). At that conference, Kilborn presented a paper based upon the previous CANMET contract. The interest that was aroused by the paper motivated Kilborn to apply for a second contract to continue the work. In the second application, the goal of developing a prototype can be described as follows:

To develop a hardware/software/application program system, operable on a modest computing facility, that would be stand-alone and would be portable into the plant to give plant personnel hands-on-access to the procedure. There was the explicit requirement that the procedure would be orders of magnitude more efficient than the one demonstrated in the previous study(2). This further implied that the mathematical programming procedure would be changed radically, and very efficient programming and computational devices would have to be employed.

Particular emphasis was placed on provisioning for high $MgCl_2$ and insoluble materials in the process streams. This provisioning would be sufficient to enable mass-energy balancing for all

potash plant circuits including facilities for solution mining and hydraulic hoisting.

The proposal called this system a B-prototype in order to distinguish it from the previous system and from a fully on-line device called a C-prototype. Although the C-prototype was beyond the scope of the new contract, an effort would be made to define possible specifications for the manufacture of such an instrument.

Summary of the Results of this Study

At the conclusion of this study the B-prototype has been developed to the following extent:

(1) A mass-energy balancing procedure has been developed for a microprocessor system.

(2) The microprocessor used is of the kind and class that is becoming commonly available in potash plants.

(3) Although the micro requires some modification and a particular specification, these extras are within the range of affordability.

(4) A clear picture of microprocessor technology has been obtained which points the way toward the development of an advanced prototype for process control in potash processing.

The mass-energy balancing procedure contains the following additional provisions:

(1) Inclusion of the complete $NaCl-KCl-MgCl_2-H_2O$ solution chemistry.

(2) Provision for insoluble material in the process streams.

(3) Identification of NaCl precipitation thresholds.

A by-product of solving the mass-energy balancing problem has been the development of a solution to non-linear programs(NLPs) of reasonably large dimension. Many of today s systems engineering problems reduce to NLPs.

Another important by-product of this study is a so-called stream processor which can be used to regulate the addition of add-back water in each effect of a potash crystallizer. This regulation both rations water addition in order to prevent NaCl precipitation, and avoids loss of recovery or high energy consumption.

Mass-energy balances have been obtained for particular, situations in crystallizer circuits at Central Canada Potash (CCP) at

Colonsay, Saskatchewan, and at Cominco Ltd. at Vanscoy, Saskatchewan.

A complete specification for the B-prototype is included in this report. Computer programs and test problems are delivered as a separate package All non-proprietary technology is delivered on 5 1/4 inch diskettes. Proprietary software and firmware licenses are obtainable at reasonable cost. Energy Mines and Resources have acquired licenses to most of this technology.

The report reviews manufacturing problems in packaging of advanced prototypes and industrial instruments for process control. The study has identified leading microprocessor candidates for special purpose applications such as the stream processor and a specific circuit mass-energy balancer. The study concludes with an outline of packaging for single board microprocessors at low unit development cost.

Recommendations

The most important phase of this development will be to apply the B-prototype to process applications in the potash industry. Several categories of application are envisaged:

(1) Conceptual and flowsheet design cases.

(2) Operational circuit evaluations.

(3) Energy debottlenecking cases.

(4) Control systems betterments.

The first step in this future program will be to make presentations to managerial and technical people at the operating mines. Such presentations will feature illustrative examples of the use of the prototype system and this will serve to increase industry awareness of the results of this work.

The second step will be to engage the operating mines in several programs which use the prototype to solve problems that are identified within their processes. This work will serve to fine-tune the B-prototype and to clarify requirements for the C-prototype.

It is Kilborn's view that an on-line instrument is a pressing requirement for the industry. This view is shared by the companies that participated in the study. It is most strongly felt by companies with a high magnesium in their ores. This results from the study conclusion that the only feasible method of on-stream analysis, in the high magnesium case, is with a complimentary on-line mass-energy balancing procedure.

Therefore, **the first recommendation** of this study is that future development should consist of the following four stages:

(1) Application and shakedown of the B-prototype.

(2) Formulation of plans and proposals for C-prototype development including economic evaluations of particular cases.

(3) Development of the C-prototype.

(4) Implimentation of standardized systems based upon the C-prototype.

At stage (2) it is believed that the C-prototype will undergo two expansions of scope, insofar as crystallization is concerned.

(1) Provision of features for process dynamics.

(2) Inclusion of features for the control of particle size analysis.

It is envisaged that the first expansion in scope will reflect a requirement for adaptation in process regulation for certain process loops. The second expansion is a recognized objective in potash research and development. Indeed, it is the subject of work that has paralleled this study (Randolf et al(10)). Moreover, it is clear that the time is drawing near for these separate directions of pursuit to be brought together.

The main result of the work to-date on crystal size control has been the development of an effective particle size analyzer and a better understanding of the kinetics of crystal nucleation and growth.

Therefore, **the second recommendation** of this study is that an effort should be made to integrate the results of this energy management and control study with recent advances in particle size analysis and control.

The third recommendation of this report is that those portions of the potash process, other than crystallization, that have a high energy dependence should be addressed. Important areas are:

. Drying and cooling of product

. Evaporation circuits

. Solution mining and hydraulic hoisting

. Compaction

The fourth recommendation is that attention be given to non-potash applications. Examples are to be found in the manufacture of industrial chemicals such as Na_2SO_4, non-chloride fertilizers such as K_2SO_4, which are attracting the interest of chemical and fertilizer producers and salt cake in pulp mills.

All of these processes have energy management problems similar to potash.

THE GENERAL MASS ENERGY BALANCING PROBLEM

The following processes occur in potash circuits which have a direct bearing upon the deportment of material and energy:

(1) Pulping or repulping.

(2) Dissolution by contact or heat exchange.

(3) Separation processes such as thickening and flotation.

(4) Evaporation.

(5) Water addition for saturation control.

(6) Steam or vapor addition.

(7) Crystallization.

(8) Precipitation.

(9) Selection or classification.

(10) Breakage.

(11) Compaction.

(12) Condensation.

(13) Reagentizing.

These are the basic physical transformations that occur in the potash process, an unusually long list for a mineral process. Individual unit processes and unit operations consist of various combinations of this list. The largest combination is the (re-)crystallization unit process which includes all items except (10) and (11) and mathematically includes all.

The above introduction is more useful than the usual flowsheet representation in the understanding of the subsequent theoretical treatment of the thermodynamics of the potash process. This is not a substitute for understanding the flowsheet, but will be helpful in following the mathematics.

The potash process can be considered to be isothermal to a fair degree of approximation where units are at atmospheric pressure and adiabatic where pressure vessels are involved. Shaft work is not considered to be a significant energy item, even though the conventional design is clearly wasteful of energy due to high plant profile. Dissipative shaft work is substantial in crushing, grinding and compaction.

Potash plants consume electricity and natural gas. The latter is the major source of plant energy, with some operations

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co-generating electricity for their own need. Potash energy consumption is a major factor in the Saskatchewan energy balance of supply and demand. Energy intensive items are drying, evaporation, crystallization, hoisting and solution mining. This energy aspect of the potash industry in Saskatchewan provides the motivation for this contract. The long range target of this work is a 10-20% reduction in process steam consumption which represents 4-8% of provincial gas consumption.

The major complication of potash mineral processing is the solubility of the ore which is connected to the high electromotivity and the low atomic weight of the alkali species that populate the process streams. Canadian potash ores contain the following minerals:

Halite	NaCl
Sylvite	KCl
Carnallite	$KCl.MgCl_2.6H_2O$
Insolubles	Principally Clay

On pulping, at all process temperatures, carnallite will enter into solution, almost immediately, unless it is occluded or entrapped by the other minerals. In some cases, the contained KCl will subsequently precipitate, if the carrier is near KCl saturation. Carnallite re-crystallization never occurs in the conventional process. Consequently, $MgCl_2$, if present, will be in solution at a level well below saturation in all cases.

$MgCl_2$ reduces the solubility of both KCl and NaCl yet it does not have a large effect on heat values. This reduction in solubility has a dramatic effect upon the carrying capacity of the water component, effectively reducing the energy efficiency of the process.

The solubility relations for alkali chlorides will be shown to be highly non-linear.

The following formalism has evolved to describe solubility, in consideration of the 13 processes outlined above:

Let x_{mj} be the physical chemical analysis of the jth process stream, in terms of the following m constituents:

m	x_m
1	NaCl in solid form as NaCl
2	KCl in solid form as KCl
3	$MgCl_2$ in solid form as $MgCl_2$
4	NaCl in solution
5	KCl in solution
6	$MgCl_2$ in solution

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7 Water including hydration
8 Insoluble materials

x_{mj} represents weight fraction, consequently:

$$\sum_{m} x_{mj} = 1 \quad \text{.....(1)}$$

which is called the consistency constraint.

u_{mj} represents mineral composition where:

m	u_m
1	NaCl in solid form as halite
2	KCl in solid form as sylvite
3	$MgCl_2$ in solid form as carnallite
4	NaCl in solution
5	KCl in solution
6	$MgCl_2$ in solution
7	Free water
8	Insolubles

If $p = \frac{\text{molecular wt KCl}}{\text{molecular wt } MgCl_2}$ and $q = 6\,\frac{(\text{molecular wt } H_2O)}{\text{molecular wt } MgCl_2}$

Then $u_1 = x_1$ $u_2 = x_2 - px_3$

$u_3 = (1 + p + q)x_3$ $u_4 = x_4$

$u_5 = x_5$ $u_6 = x_6$

$u_7 = x_7 - qx_3$ $u_8 = x_8$

and $u_{jm} = x_{jm} = 1$

and $x_8 + u_m = C_w = x_1 + x_2 + (1 + q)x_3 + x_8$

where $100C_w$ is the weight percent solids.

In certain mass balancing systems subtleties of the u representation are ignored causing serious computational errors.

It will be necessary to employ four specific gravities in the subsequent analysis. These can be interpreted in terms of mineral specific gravities. The fundamental R values are:

R the specific gravity (s.g.) of the slurry stream

R_s the s.g. of the solids

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R_b the s.g. of brine

R_w the s.g. of water

R_s is computed from the formula:

$$R_s = \frac{R_h u_1 + R_s u_2 + R_m u_3 + R_i u_8}{u_1 + u_2 + u_3 + u_8} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where R_h,R_s,R_m, and R_i represent the s.g. values for the halite, sylvite, carnallite and insoluble components of the slurry stream and the u values are volumetric in formula (2). The s.g. values vary from mine to mine due to variations in the crystalline structure of the ore, the presence of impurities, and variations in clay composition.

Brine density varies with temperature and composition. The study has determined an empirical relationship between these variables.

For a slurry stream the following dual relationship must be satisfied:

$$\frac{R_s(R - R_b)}{R(R_s - R_b)} = C_w = u_1 + u_2 + u_3 + u_8 \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Equations (3) must be preserved in order to reflect mass conservation in terms of the R value.

The Incident Matrix

As in the previous study, the process flowsheet will be described in terms of nodes and streams in the form of an **incident matrix** m_1. The concept of node is roughly equivalent to the chemical engineering concept of unit operation. m_1 will have a matrix element +1 if the process flow is into the node, a value -1 if the flow is out of the node and 0 if there is no connection. Nodes can be thought of as consisting of a sub-network of the thirteen (or more) binary process transformations that were highlighted at the beginning. These sub-networks describe the infra-topology of the circuit so that the diagonals of m1 can be expanded to incorporate greater circuit detail or contracted in order give a more simplified view of the circuit. The branch of mathematics known as topology thus provides a means of effecting transformations from one level of circuit detail to another.

Process Constraints

The process constraints are the equality and inequality relations that must be obeyed in order to conform to the physics and chemistry of the process. These physical laws are embodied in the following principles:

(1) Conservation of mass.

(2) Conservation of energy.

(3) The equations of state of the process.

(4) The remaining laws of thermodynamics.

For process streams the solubility relationship is the appropriate equation of state. For vapors this equation of state is summarized by steam tables.

Process flows are described by four stream vectors:

D_j mass flow rate for the total of all stream species other than water

D_j^W mass flow rate of the total water component

D_j^P mass flow rate of the total stream (pulp flow rate)

F_j volumetric flow rate

These stream vectors are interrelated as can be seen from the following relations:

$$D_j^P = RF_j$$
$$= D_j + D_j^W \quad \ldots\ldots(4)$$

Conservation of Mass

Conservation of mass in a circuit gives the matrix equation:

$$m_1 D^P = 0 \quad \ldots\ldots(5)$$

Equation (5) is an understatement of conservation of mass since:

$$m_1 D^P (x_k + x_{k+3}) = 0 \quad k = 1,2,3$$
$$m_1 D^W = 0$$
$$m_1 D^P x_8 = 0 \quad \ldots\ldots(6)$$

must also be true. It can be shown that equation (1) together with equations (6) reduce to equation (5). This reduction will be important later on in the determination of problem degeneracy.

Conservation of Energy

The enthalpy of a process stream is defined as:

$$H = U + PV \quad \ldots\ldots(7)$$

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where U is the internal energy and PV is the shaft work. Pressure vessels in the potash process, to a first approximation, are adiabatic and hence isenthalpic. Moreover, the first partial derivative of H wrt temperature, along an isobar, is c_p, the specific heat at constant pressure.

Enthalpy conservation and energy conservation are thus synonymous in potash processing. A convenient computation of stream enthalpy per unit mass (specific enthalpy) is:

$$H_j = \sum_m u_{mj} h_{mj}$$

where $$h_{mj} = (c_p)_{mj}(T_j - T_{ref}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

is the specific enthalpy of the stream component. T_{ref} is a reference temperature which is usually taken as zero degrees celsius.

Equation (8) is correct for solution components if an additional term corresponding to the heat of solution is added in the computation of h_{mj}.

The following conservation relation holds:

$$m_1 D^P H = 0$$

Another form for conservation of enthalpy is:

$$m_1 D^P u^T h = 0$$

where u^T is the transpose of the u matrix. In matrix algebra the order of multiplication is important. The above equation illustrates an important difficulty in solving linearized problems, because it cannot be converted to the form:

$Au = 0$ where A is a linearized matrix.

This is aside from the non-linearity due to the product form $D^P u^T$.

The Main Constraint Set

The following set of equations:

$$\sum_m x_{mj} = 1$$

$$m_1 D^P (x_k + x_{k+3}) = 0$$

$$m_1 D^P H = 0$$

$$m_1 D^W = 0$$

$$m_1 D^P = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

consists of $M = 6n_p + n_g$ equations in $N = 8n_p - n_g$ unknowns, where n_p is the number of streams in the process and n_g is the number of nodes. For example, in the case of the CCP crystallizer circuit there are 180 equations in 212 unknowns.

Such a system does not have a unique solution. However, the set of equations (10) is not yet a complete description of the set of process constraints because the solubility relations are not yet defined.

Solubility relations for NaCl and KCl are respectively:

$$wU_1 \geq x_4$$

$$wU_2 \geq x_5 \quad \ldots\ldots\ldots\

Possibly 20 of these 36 constraints will bind the solution. These are the cases of NaCl saturation, KCl saturation or both. Therefore, the number of degrees of freedom is of the order of

NDEG = 212 - 180 - 20 = 12

This is an estimate of the minimum measurement set that is required to define a balance. In practice it is well below an acceptable measurement set because each measurement is imperfect.

The Concept of a Coherent Balance

The following measurements can be obtained from a potash circuit:

Slurry streams	Analysis Volumetric flow Specific gravity Temperature
Brine Streams	Analysis Volumetric flow Temperature
Water Flow	Volumetric flow Temperature
Steam	Mass flow Temperature Pressure
Vapor (saturated)	Temperature (Pressure*)

* Pressure, temperature and solution composition are related through a solution-vapor equation of state.

Conversions are performed in order to transform stream measurements to equivalent estimates for the following variables.

Variable	Measurement	Statistic
D_j^p	$\underline{D}_j^p$	s_j^p
D_j^w	$\underline{D}_j^w$	s_j^w
Y_j	$\underline{Y}_j$	s_j^y
x_{mj}	a_{mj}	s_{mj}

$\underline{D}_j^p$ is the measured value of pulp flow in tonnes/hour for the jth stream.

s_j^p is the standard error of measurement of pulp flow or

some other estimate of the total error of measurement of pulp flow.

Similar nomenclature applies to the water flow, dilution and composition. Dilution is defined as:

$$y_j = D_j^w/D_j = (1 - C_v)/(R - (1 - C_v) \quad \ldots\ldots\ldots\ldots(14)$$

where C_v is the volume fraction of solids for the jth stream. A coherent balance is a solution to the constraint functions (equations plus inequalities) which is minimal with respect to:

$$J = \sum_j((D_j^p - \underline{D}_j^p)/s_j^p)^2 + \sum_j((D_j^w - \underline{D}_j^w)/s_j^w)^2 + \sum_j((y_j - \underline{y}_j)/s_j^y)^2 + \sum_{j,} ((x_{mj} - a_{mj})/s_{mj})^2 \quad \ldots\ldots\ldots(15)$$

Such a solution can be shown to be unique provided that certain topological relations are satisfied for a given circuit.

The Meaning of the Coherent Balance

Minimizing (15) subject to equations (10) and respecting inequalities (11) satisfies the following physical objectives:

(1) Mass and energy are conserved.

(2) Solubility relations are satisfied. However, there is the proviso that certain constraints bind in the presence of solids.

(3) A solution respecting the above is minimal in the least squares sense.

(4) If the measurement set is chosen properly and measurement errors have normal statistics, the solution will be a maximum likelihood estimate of the current state of the process.

(5) As the process approaches steady state, under all the above circumstances, the solution will approach thermodynamic equilibrium.

Comments On the General Problem

The minimization of (15) subject to equations (10) and (11) is an enormous computational task, requiring a super-computer for circuits of moderate complexity such as the CCP crystallizer. The reasons are as follows:

(1) The problem has a high degree of dimensionality (180 constraints and a 212 variable objective function in the CCP case).

(2) There are quite a few non-linear equality constraints.

(3) There are 36 inequality constraints that are non-linear.

(4) The objective function is non-linear in the dilution terms and quadratic in all others.

Mathematical problems such as this have been designated as non-linear programs and the literature contains many formulations that have been considered to be numerically unsolvable by practical affordable means. A large percentage of these problems are energy optimization problems.

The goal of this study was to be able to obtain solutions, to the mass-energy problem on a modest computer within the elapsed time of several hours. As formidable as this task might have seemed, the goal has been achieved by configuring a microcomputer to solve the non-linear program for less than 50 variables. Thus the overall problem became one of decomposing the general problem into a set of sub-problems and developing an effective microcomputer package to solve them, in a prescribed way.

THE CRYSTALLIZER PROBLEM

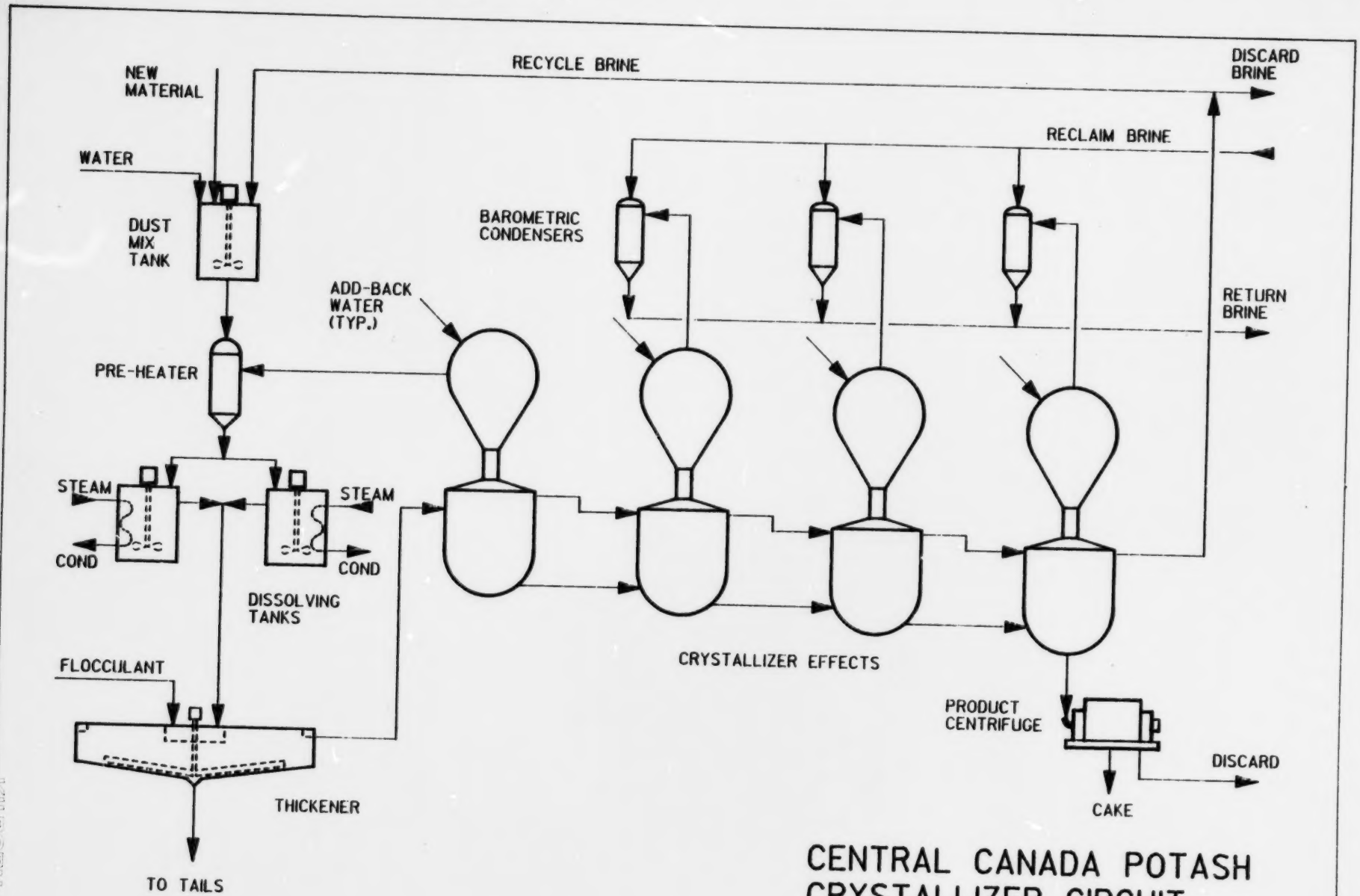
The following discussion deals with the principle case of the previous study. This is the potash crystallizer circuit. Similarity exists with a potash crystallizer, a potash evaporator and an Na_2SO_4 circuit, or any other industrial crystallizer. The techniques employed in the ME procedure are applicable to all cases due to the generality of the topological approach that is used in the model.

Figure I and II show the process flowsheets for the CCP crystallizer and the IMC K-2 crystallizer. Figures III and IV show the network topology of these two circuits that is used to construct the incident matrix. The circuit in Figure II does not include the high KCl circuit which provides additional purification for some of the IMC product.

The CCP circuit was explained, in the previous study report. The reader is encouraged to review (2) and (6). Both circuits (IMC and CCP) perform similar functions within the overall process. This function meets the objective of recovering KCl values that would otherwise go to tails were it not for the crystallizer.

Materials from dust collection and effluent flotation, as a slurry , are combined with recycle mother liquor in a so-called dust-mix tank. Discharge from the dust-mix tank has a relatively low temperature which, in the CCP circuit, serves as a means of condensing overhead vapor from the first effect crystallizer as well as increasing the sensible heat of the discharge stream. Some dissolution occurs in this first barometric condenser or preheater, as it is often called. However, the principal unit for dissolution is the dissolver(s). This is normally a twin unit that employs counter-current heat exchangers that use process steam to raise the temperature of the dust-mix tank discharge slurry to effect dissolution. Most of the soluble KCl will enter into solution and much of the NaCl will remain as solids due to the differences in the slopes of the KCl and NaCl solubility curves. Dissolvers return measurable quantities of condensate through a trap. The measurement of this flow provides information that can be used to calculate the exchanger heat transfer coefficient if a mass-enthalpy balance is obtained in the main portion of the vapor-solids circuit. This helps to identify fouling and plugging.

Dissolver discharge is clarified, eliminating waste to tails in a hot thickener. Clarified overflow from the thickener should be near KCl saturation and below NaCl saturation, as it is fed to the first "effect" of the crystallization circuit. Each crystallizer effect is functionally identical but there are only three at IMC in each main circuit, whereas there are four at CCP.
The overhead vapor from a crystallizer effect (shown as Figure V) comes into contact with cool brine in a barometric condenser (CCP 1st effect contacts dust-mix slurry) and creates a vacuum in the crystallizer which causes the magma to boil. The combined effects



CENTRAL CANADA POTASH CRYSTALLIZER CIRCUIT

FIGURE I

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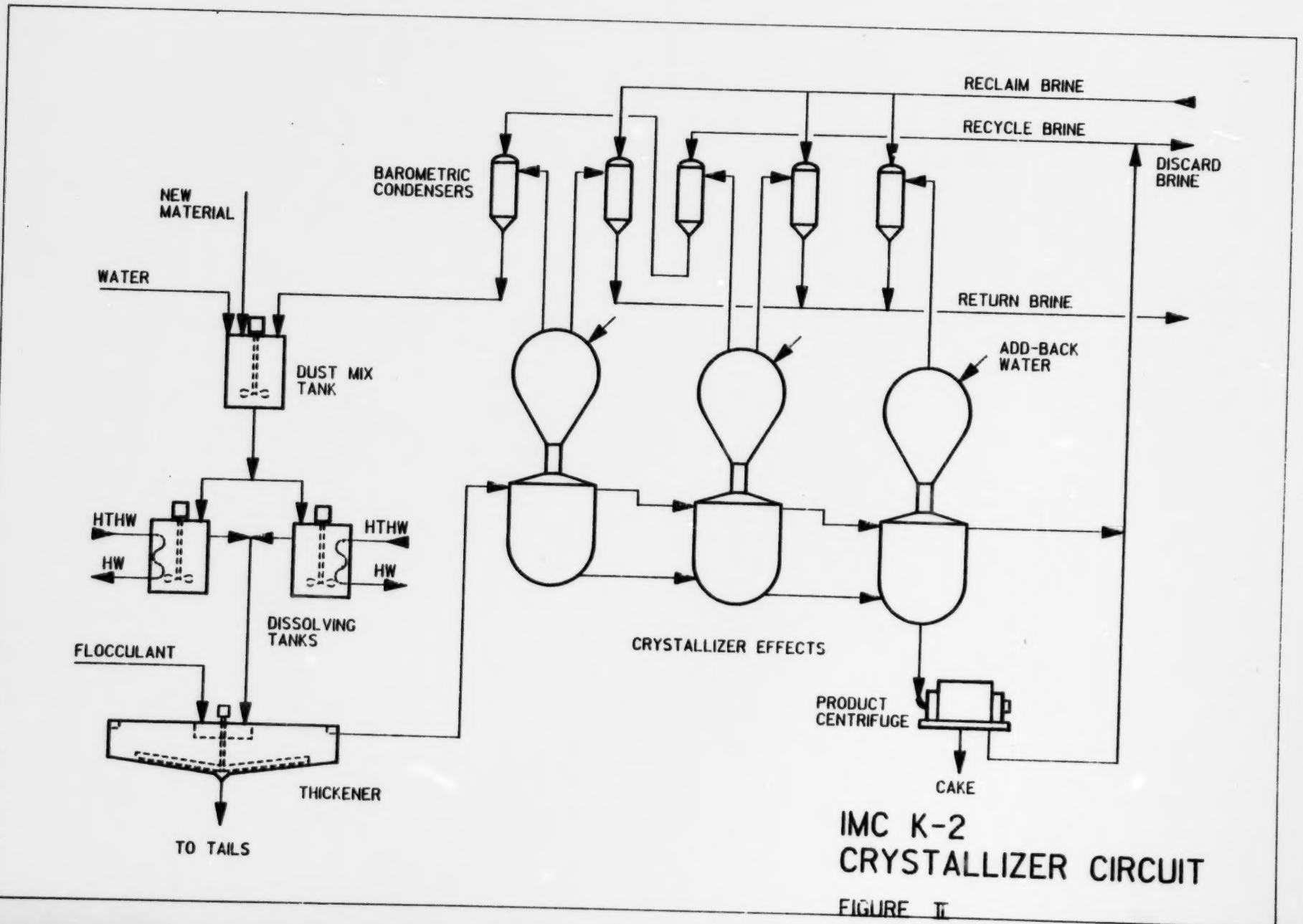

IMC K-2
CRYSTALLIZER CIRCUIT

FIGURE II

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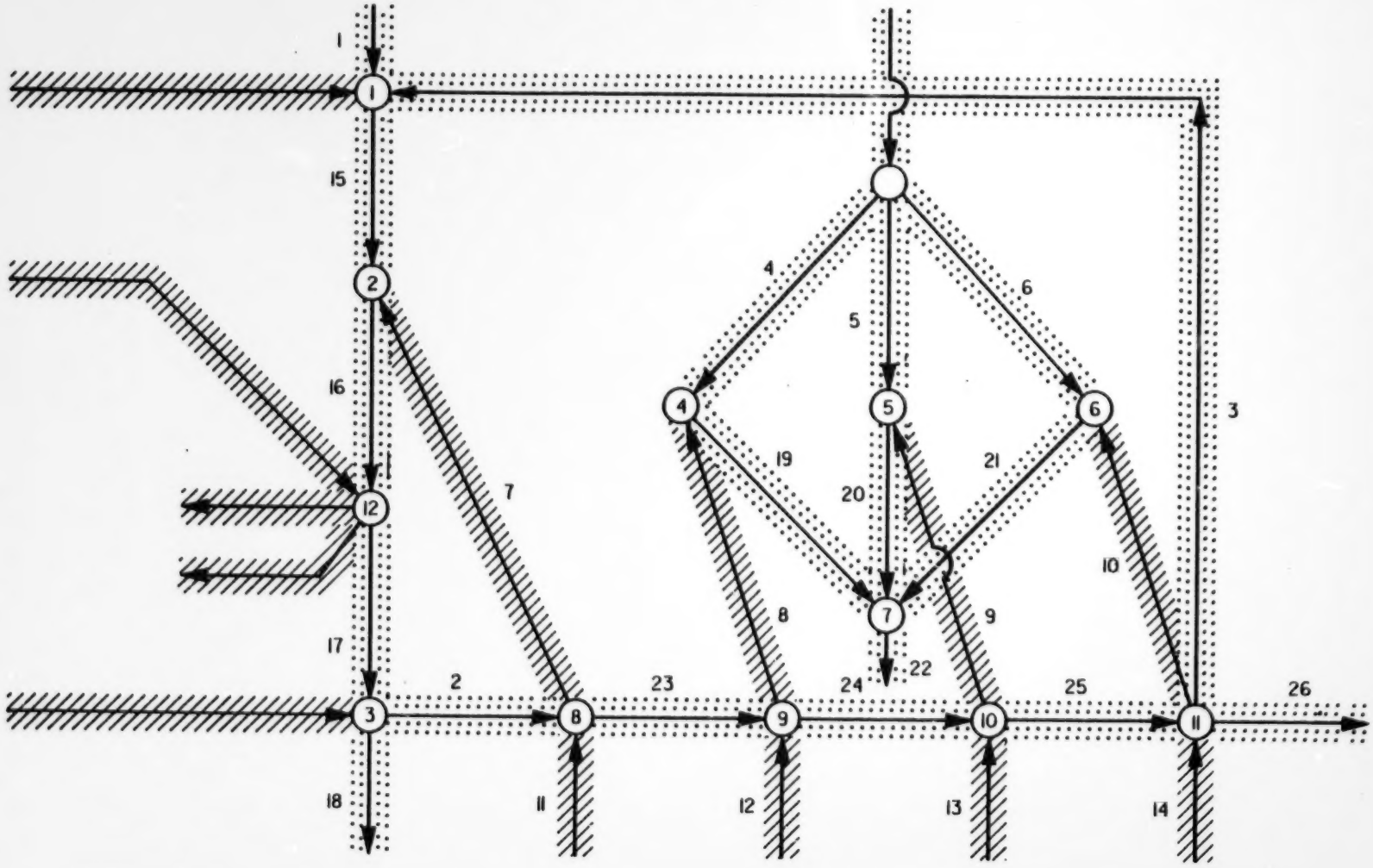

CENTRAL CANADA POTASH CIRCUIT TOPOLOGY

FIGURE III

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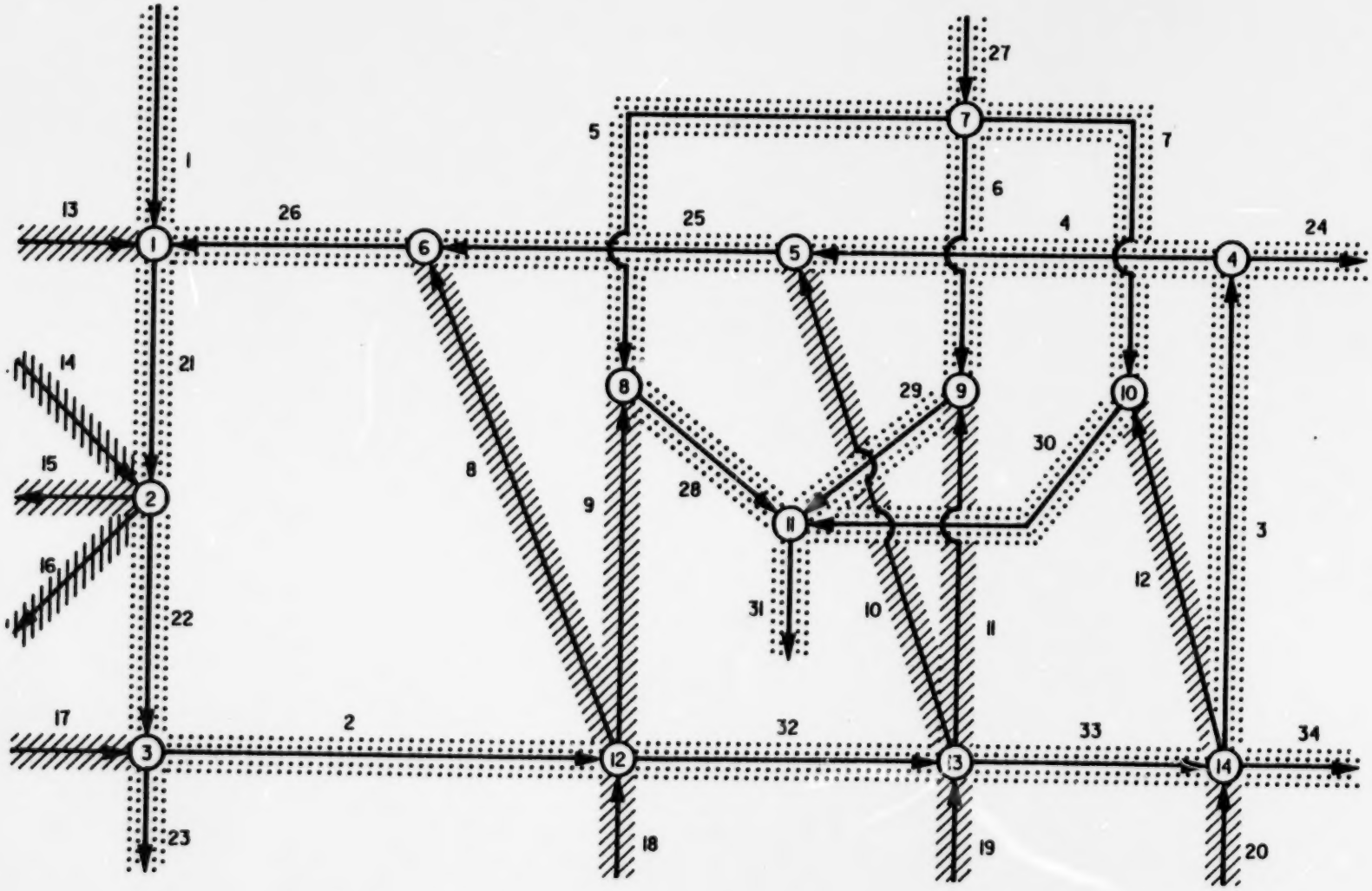

IMC K-2
CIRCUIT TOPOLOGY

FIGURE IV

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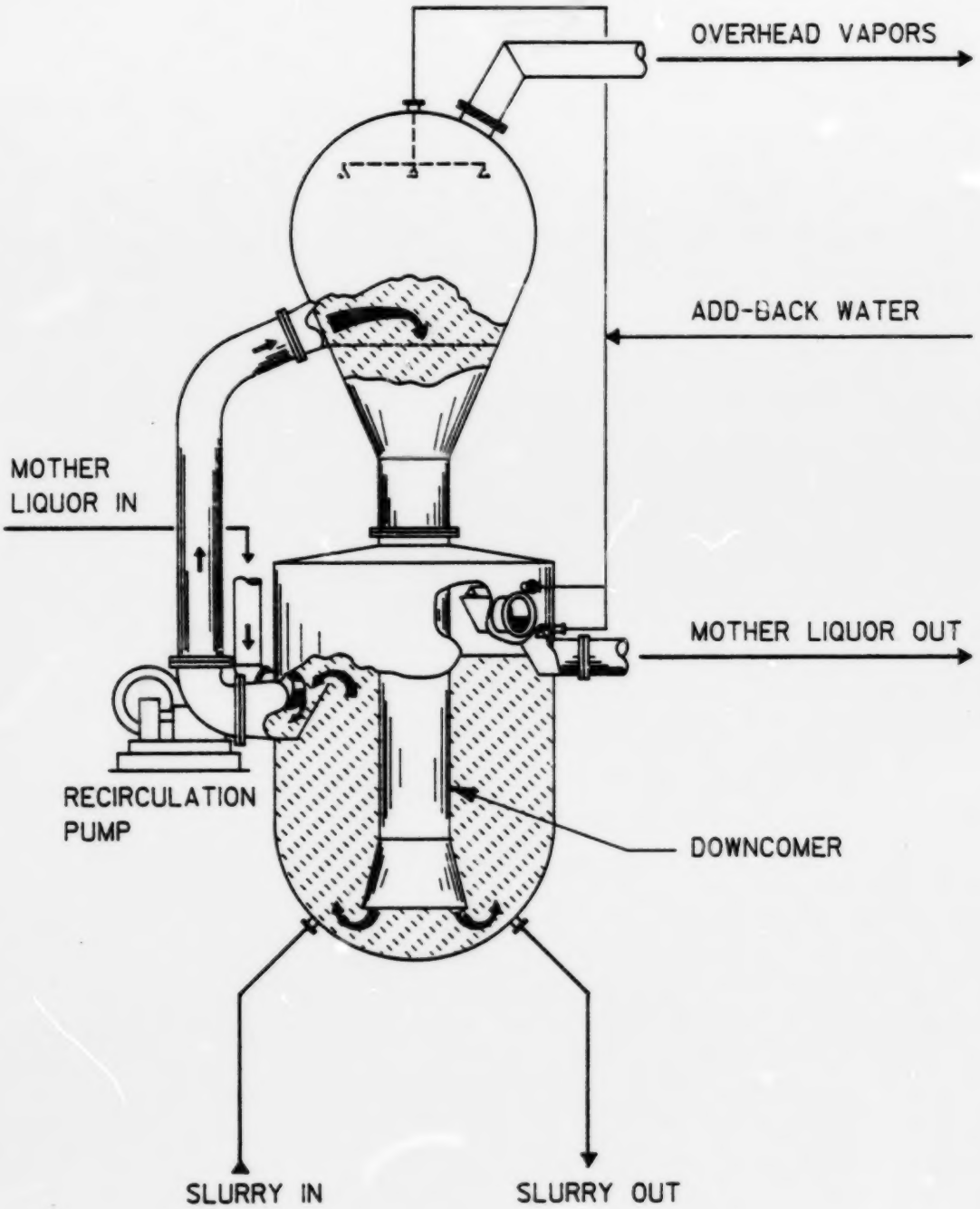

CRYSTALLIZER EFFECT

FIGURE V

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of boiling and evaporative cooling are conducive to crystallization in a zone of super-saturation at the top of the magma. The system is agitated to promote mixing by recirculation around the enclosed system using an immersed pipe called a downcomer.

Multi-stages of crystallization progressively lower the temperature of inter-stage effluent streams. The lower vessel effluent has a higher crystal load and ideally, the upper stream should be a relatively clear mother liquor. Densifiers may be employed after the final stage in order to improve clarification.

The presence of significant levels of $MgCl_2$ in the IMC circuit necessitates additional barometric driving force. This is accomplished by employing a more complex arrangement of barometric condensers on the first two effects which enables the cool recycle mother liquor to contact the overhead vapors from the first two effects. Reclaim brine is also used as an overhead vapor coolant. Thus, in the IMC circuit, recycle mother liquor is preheated before it arrives at the dust mix tank.

In general, saturation control is effected by the addition of water at key points in a potash circuit. These additions may be at the dust-mix tank, at each effect or at some other point in the process recycle loop. These water additions are to make up for evaporation in order to control saturation and to prevent unwanted NaCl crystallization. The profile of water addition has a profound effect upon product rate, product quality and energy consumption.

Further Comparisons

Figures I to IV indicate that the CCP circuit is more complex than the IMC circuit because at CCP there are four effects rather than three. However, a topological analysis will show that they have similar complexity even though they appear quite different.

A review was made of the IMC high KCl circuit and it was proven that it can be separated from the main crystallizer circuit. Thus two sub-circuits only need be solved separately with a third simple balance resolving the interactions according to a treatment which considers each circuit as a single node in a two node circuit.

By this means it has been proven possible to solve circuits of twice the complexity of Figures I and II with little more than twice the computer time. The same device would work for the evaporator/crystallizer combinations that are used in solution mining. However, it was not found possible to reduce the complexity of the basic circuit because of the interaction caused by the mother liquor recycle.

CCP and IMC have different operating practices with respect to recycle brine. At CCP, large quantities of 4th stage mother liquor are frequently discarded to the brine storage, whereas at

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IMC this is not done. The energy consumption aspect of this difference in operating practice is controversial.

Topological Considerations

Study of the crystallizer problem has indicated several means of improving the performance of the mass-balancing procedure. A topological device was discovered for the numbering of nodes and streams which always enables the construction of an incident matrix with the following structure:

$$m_1 = (m_a | m_b | m_c)$$

The vertical bars indicate a partitioning into three matrices:

(1) The matrix m_a has dimensions $n_a \times n_q$

where n_a = number of slurry streams - number of slurry nodes.

The columns of m_a form a linearly independent basis for the determination of the solids vector D_j. Let this be called D_j^a. At CCP and IMC this consists of six streams.

Table I

j	CCP	IMC K-2
1	New Material	New Material
2	Feed to the 1st Effect	Feed to the 1st Effect
3	4th Stage Mother Liquor	3rd Stage Mother Liquor
4	Reclaim Brine to 2nd Effect	Reclaim Brine to 1st Effect
5	Reclaim Brine to 3rd Effect	Reclaim Brine to 2nd Effect
6	Reclaim Brine to 4th Effect	Reclaim Brine to 3rd Effect

(2) The columns of the matrix m_b correspond entirely to water, steam or vapor streams. The matrix has dimensionality $n_b \times n_q$. The matrix m_b is such that the partitioning:

$$(m_a | m_b) = m_d$$

is a linearly independent basis for the determination of the circuit water vector D_j^w. Moreover:

$$n_d = n_a + n_b = n_p - n_q$$

(3) The matrix m_c will be non-singular which implies that the inverse m_c^{-1} always exists. Moreover, for certain circuits the matrix can be made lower triangular, a feature that enables a substantial reduction in matrix inversion times on a computer. A notable exception is the IMC K-2 crystallizer circuit which has at least one non-zero element above the diagonal. This feature marks the extra energy

coupling associated with the barometric condensers on the recycle brine.

The matrix m_c^{-1} is required in various steps throughout the mass-energy procedure. In some cases it is in combination with the vectors D, D^p and H. It has been possible to invert these matrices in very short times using a combination of software and hardware. 12 x 12 matricies are inverted in less than 12 seconds which is ten times faster than similar matrix operations performed on the large mainframe in the previous study.

The importance of this development follows from an examination of the mass balancing relations:

$$m_1 D = 0$$

$$m_1 D^w = 0$$

Since the basis vectors D^a and D^{wd} are linearly independent, the non-basic sets D^c and D^{wc} can be calculated as follows:

$$D^c = -m_c^{-1} m_a D^a$$

$$D^{wc} = -m_c^{-1} (m_a | m_b) D^{wd} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

The NLP algorithm that works best is a gradient search procedure and, consequently, equation (16) causes a dramatic reduction in the dimensions of this procedure. This results in a significant reduction in the total amount of computer time.

The topological analysis underlines the importance of measurement on the streams listed in Table I. Measurements on these streams have maximum sensitivity in terms of their impact on the solids deportment aspect of the mass energy balance.

The water vector presents a different situation because the dimension of the basis is 14 rather than 6. If these 14 streams are ranked in order of specific enthalpy, the topological procedure yields the H_2O streams that have maximum impact on the enthalpy balance. These are the overhead vapor streams, the dissolver steam and the dissolver condensate streams.

Reclaim brine thus becomes a crucial measurement in the definition of the circuit energy balance. None of the circuits examined in the study have instruments for the measurement or the regulation of reclaim brine to the barometric condensers. Barometric driving force provides principal motive power for a crystallizer circuit, but unfortunately, there is little provisioning for monitoring or regulation.

The Solution Chemistry of the NaCl-KCl-$MgCl_2$-H_2O System

The solubility of either NaCl or KCl, in a potash stream is adversely effected by relatively small amounts of $MgCl_2$. In Saskatchewan and New Brunswick the source of $MgCl_2$ is the mineral carnallite ($KCl.MgCl_2.6H_2O$), which is highly soluble. It is prevalent in the Esterhazy member of the Prairie Evaporite.

Information on the effect of $MgCl_2$ on KCl and NaCl solubility is limited to the work of D'Ans(3) which covers the joint saturation effect. D'Ans work does not include the so-called undersaturation effect which occurs when either NaCl or KCl are below saturation. Central Canada Potash have supplied data to explain this effect for a magnesium free environment. From dimensional analysis and phase rule considerations these effects should combine according to product formulae:

NaCl: $$U_1(z_5,z_6,T) = f(z_5,T)X_1(z_6,T)$$

KCl: $$U_2(z_4,z_6,T) = g(z_4,T)X_2(z_6,T) \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

The terms X_1 and X_2 follow the D'Ans data and Tables I and II show the results of the non-linear least squares fitting of the D'Ans data.

Table II
Non-Linear Least Squares Fit to the NaCl Joint Saturation Data By the Form

$$X_1(z_6,T) = (b_0 + b_1 z_6)\exp(b_2 T)$$

	Parameters	Asymptotic Standard Errors
$20 \leq T \leq 100$	$b_0 = 23.3238$	.1341
	$b_1 = -1.0763$	.0116
	$b_2 = -.00161$	.0001
$100 < T \leq 220$	$b_0 = 22.2354$	.1303
	$b_1 = -.93187$	.0084
	$b_2 = -.00133$	.0000

T - Fahrenheit Temperature

Table III
Non-Linear Least Squares Fit to the KCl Joint Saturation Data By the Form

$$X_2(z_6,T) = (b_0 + b_1 z_6) + (b_2 + b_3)T$$

Parameters	Asymptotic Standard Errors
$b_0 = 4.9102$	.0458
$b_1 = -.1626$	.0093
$b_2 = .08049$	.0003
$b_3 = -.001838$	.0001

Since these formulae explain close to 100% of the variance of the D'Ans data it appears that the forms chosen correspond exactly to D'Ans' working formulae.

The determination of the undersaturation factors f and g was done by setting $z_6 = 0$ and applying equations (17) with the above relations inserted for X_1 and X_2. The results of the non-linear least squares fitting[1] is shown as Tables IV and V.

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Table IV
Non-Linear Least Squares Fit to KCl Undersaturation Data
By the Form

$$f(z_5,T) = (a_1 + a_2 z_5)\exp((a_2 + a_3 z_5)T)$$

Parameters	Asymptotic Standard Errors
$a_1 = 1.1377$	.00416
$a_2 = -.02508$	.00044
$a_3 = .001624$	.00004
$a_4 = -.00133$	.000004

Note: There are 49 degrees of freedom in this fit and the explained variance is 99.99%.

Table V
Non-Linear Least Squares Fit to Undersaturation NaCl Data
By the Form

$$g(z_4,T) = (a_1 + a_2 z_4)T^{(a_3 + a_4 z_4)}$$

Parameters	Asymptotic Standard Errors
$a_1 = 13.5753$	.5990
$a_2 = -.4849$	.0263
$a_3 = -.4364$	.0119
$a_4 = .006639$	.0007

Note: There are 49 degrees of freedom and the explained variance is 99.9%.

The fits presented in Tables IV and V suggest that the parameters have fundamental significance and that extrapolation onto the general $U_1 - U_2$ hypersurface is warranted.

The resultant expressions for U_1 and U_2 have been programmed for use on microcomputers at IMC. Development Engineers at both K-1 and K-2 plants have been using the procedures in process analysis work. Similar aids have been made available to Kilborn Metallurgists. Comments on the apparent validity are so far favorable. However, these formulae can be refined through application of the mass-energy balancing procedure itself (see section on process identification).

It is also suggested that a program of measurement be undertaken at a scientific laboratory to refine these formulae on undersaturated brines with high KCl. Even a few measurements would be useful in conducting tests of the hypothesis that the solubility expression (17) has a product form. This experimentation would be difficult as temperature and salinity controls would be required to implement a factorial design.

The Concept of Brine Condition

The previous study introduced the concept of brine condition which is summarized in Table VI. Furthermore, this table shows how the brine condition corresponds to the mathematical nature of the solubility constraints.

Table VI
Constraint Condition vs Brine Condition(BC)

	KCL CONSTRAINT	NaCl CONSTRAINT
KCL SAT NaCL SAT	BINDING/LINEAR (BC = 1)	BINDING/LINEAR (BC = 1)
KCl USAT NaCl SAT	UNBINDING/LINEAR (BC = 3)	BINDING/NON-LINEAR (BC = 3)
KCl SAT NaCl USAT	BINDING/NON-LINEAR (BC = 2)	UNBINDING/LINEAR (BC = 2)
KCl USAT NaCl USAT	UNBINDING/NON-LINEAR (BC = 7)	UNBINDING/NON-LINEAR (BC = 7)

The most common condition in a crystallizer circuit is BC = 2, in most other potash circuits BC = 1. The above table shows where the solubility constraints bind and where they are non-linear. Brine conditions 1 and 3 are to be avoided in a crystallizer beyond clarification because then NaCl crystals can form. Brine condition 1, if it exists, in the crystallization phase is transitional between brine condition 2 and 3 and corresponds to switching between the binding of the non-linear KCl constraint and the non-linear NaCl constraint. However, optimum control demands that the latter condition be just avoided. The fact that either side of the linear transitional condition is non-linear indicates that a discontinuity exists. This turns out to be the energy discontinuity that results from the difference in the heats of solution of NaCl and KCl.

The energy discontinuity was recognized as a potentially serious problem for the numerical convergence of the mass-energy procedure because the final solution will show binding solubility constraints in regions where the second partial derivative have singularities. Second partial derivatives of the enthalpy

constraints play a role in the convergence process of the non-linear programs of the overall procedure. The problem is compounded in the cases with 20 or more solubility constraints.

THE POTASH STREAM PROBLEM

The satisfaction of consistency and solubility is a sub-problem to the overall procedure. Given a measurement of composition on a potash slurry stream the following information would be available:

$$x_{NT},\ x_{KT},\ x_{MT},\ R,\ T$$

which consists of measurements of total NaCl, KCl and $MgCl_2$ plus density and temperature. This would be the final output of an on-stream analyzer or the bottom line of an assay certificate.

The potash stream problem is defined by the following constraints:

$$x_1 + x_4 = x_{NT} \quad \text{.....(a)}$$

$$x_2 + x_5 = x_{KT} \quad \text{.....(b)}$$

$$x_3 + x_6 = x_{MT} \quad \text{.....(c)}$$

$$\frac{R_s(R - R_b)}{R(R_s - R_b)} - x_1 - x_2 - (1 + q)x_3 - x_8 = 0 \quad \text{.....(d)}$$

$$wU_1 \geq x_4 \quad \text{.....(e)}$$

$$wU_2 \geq x_5 \quad \text{.....(f)}$$

$$U_3(x_1, x_2, x_3) = 0 \quad \text{.....(g)}$$

Equations (a) to (c) partially describe consistency, equation (d) defines specific gravity, hence total mass consistency and equations (e) to (g) describe solubility. Equation (g) is a contingent constraint that comes into play when carnallite remains entrapped in undissolved ore particles. The presence of insol in significant amounts is used to trigger the contingency. A possible form for U_3 is:

$$\frac{x_{MT}}{x_{NT} + x_{KT}} - a1\frac{x_3}{x_1 + x_2} = 0 \quad \text{.....(23)}$$

where a1 is a multiplicative constant of the order of .6.

The variables x, R and T consists of nine unknowns which is three more than the number of constraints. However, there are the physical restrictions that $x_m > 0$ and $R > 1$.

Although the problem appears to be straight forward, such is not the case because the uniqueness of the solution depends upon the brine condition. Thus it is necessary to formulate an objective function to be minimized in order to obtain a meaningful and

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consistent vector x,R,T. From the practical point of view there are also limitations caused by truncation and round-off error.

The objective function chosen is a maximum likelihood approximation of the measurement error. Let us suppose that an estimate of experimental error exists:

$$s_x, s_R, s_T$$

If these errors have normal statistics then a maximum likelihood estimate of the full composition vector x,R,T is obtained by the minimization of:

$$J = ((x_1 - \underline{x}_1)/s_1)^2 + ((x_2 - \underline{x}_2)/s_2)^2 + ((x_3 - \underline{x}_3)/s_3)^2 + ((R - \underline{R})/s_R)^2 + ((T - \underline{I})/s_T)^2 \quad \text{.....(25)}$$

The underscores indicate measured values of the estimated values.

The partial derivative of J with respect to temperature revealed a low sensitivity. This variation is so much less than experimental uncertainty that it may be ignored. Nevertheless, temperature must be measured on every stream, since it enters into the solubility relationship.

Measurements of R are often of little value in defining the composition of a potash stream because in some slurry streams, (a crystallizer, for example) R represents R_b to a greater extent than R_s. Therefore it is important to have a model of R_b that reflects the temperature and saturation effects of brine. The R_b model developed for this study was developed by least squares analysis of measurements performed by the Saskatchewan Research Council. The formula is:

$$R_b = 1.2315 + 0.00001125T + 0.09755(x - x_s)$$

where $x - x_s$ is the solution undersaturation on an equivalent NaCl basis.

The problem defined above is a non-linear program and this mathematical program was addressed first, because it represents most of the features of the overall problem, second because it is tractable, and third because of its importance.

The pursuit of this particular non-linear program was motivated by technical and project management considerations which were:

(1) Develop and test a workable NLP subroutine.

(2) Study the numerical/analytical impact of various constraint types.

(3) Develop techniques and criteria for accelerating NLP

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problem convergence.

(4) Develop an algorithm for stream analysis that can be used for analysis, data reduction and process control.

Item (4) is most significant and has led to an algorithm for adaptive control that shows great promise.

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POTASH PROCESS CONTROL AND THE B-PROTOTYPE

The foregoing goals lead to independent dissertations in this report. The NLP is described in a general manner below and considered in detail in the prototype technology section.

The General Non-Linear Programming Problem

The general NLP addresses the minimization of a non-linear function of n variables x_i.

$$F(x_1, x_2, \ldots x_n)$$

subject to:

$$G_k(x_1, x_2, \ldots x_n) \geq 0$$

$$H_k(x_1, x_2, \ldots x_n) = 0$$

$$x_i \geq 0$$

The set of constraints G_k are inequalities and the set H_k are equalities in the following discussion. The significance of this difference cannot be overemphasized.

A solution is obtained by creating another objective function P which is called a penalty function. In this study P assumed the form:

$$P = F + \sum_k r \ln G_k + \sum_k H_k^2 / r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

where the parameter r has been introduced and will assume the following values:

$$r_0 > r_1 > r_2 > \ldots\ldots > r_n$$

r_n vanishes in the limit as n becomes large.

By varying r in the above manner a series of sub-problems are solved which will cause the constraints to be satisfied while minimizing F. However, in the stream analysis problem the mere satisfaction of the inequality constraint is not enough. The constraint must bind according to the rules of Table VI. This is accomplished by seeking values $\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$ based upon total mineral content so that saturation will be forced wherever necessary. The program logic requires a preliminary estimate of brine condition, which need not be correct and then arrives at the correct brine condition when a mass-energy balance is obtained.

The above procedure enables the detection and correction of an out-of-kilter brine composition at each stage of a crystallizer, evaporator etc. by calculation of the required water addition to establish an operating point just below NaCl crystallization.

This development is an example of a functional specification for the C-prototype which would be only one of a list of regulatory and supervisory tasks for that on-line processor.

On-Stream and Laboratory Analysis of Process Streams

Composition measurement is crucial to the monitoring and control of a potash crystallizer or any other energy intensive section of the potash process.

The backbone of on-line measurement and control has been x-ray fluorescence which employs the irradiation of the stream sample with hard x-rays causing vacancies in the electron shells of the target atoms. When the excited atoms return to their ground state energy levels, secondary or fluorescence radiation is emitted which is of a different frequency and hence different energy than the incident irradiation. Thus the sample is said to fluoresce. Each element of the sample has a different fluorescence energy spectrum and the combination of a sodium iodide scintillation detector and a pulse height analyzer measures the energy spectrum of the fluorescence radiation. After applying inter-element corrections the system gives a complete breakdown of the elemental composition of the sample plus the sample density as well.

In a potash stream the atomic weights of all the elements are much lower than that of a base metal stream. These lighter elements do not fluoresce with sufficiently high intensity to enable the detection system to discriminate with sufficient accuracy for control purposes. Thus far, no instrumentation vendor has been able to produce an on-stream analyzer that will meet even minimum specifications for control, particularly if Mg figures into the analysis requirement.

However, some progress has been made in potassium measurement. Naturally occurring potassium contains a fixed abundance of the radioactive isotope K^{40} which is an emitter of beta and gamma radiation. Attempts to measure beta activity as a means of determining potassium composition have not been successful. However, the 1.4 Mev gamma ray from K^{40} has provided a means of detection of the K population in a sample using techniques similar to that employed in x-ray fluorescence. This type of instrument is being installed at various plants throughout the potash industry.

CCP use a K^{40} analyser on streams where the brine condition is equal to one. These are conditions of joint saturation and moreover, the $MgCl_2$ level in these streams is negligible. Under these circumstances the instrument works well. However, the data reduction procedure employed by the vendors could be improved even in the CCP case by using the stream processor of this study to effect a more accurate definition of solution and solids components.

The problem centers around the density measurement which is a source of error propagation. The density measurement is obtained through the use of an independent Cs^{137} calibration source. The attenuation of the resultant beam by the sample is used to define the stream specific gravity. The associated temperature measurement is then used to define the level of NaCl and KCl in solution. Since the primary measurement defines the total KCl, the density measurement can then be used to define the total NaCl if brine density and solids density models are employed. This procedure breaks down unless the following conditions are met:

(1) Accurate solubility, brine specific gravity and brine density models are assumed.

(2) Brine corrections are made for KCl and NaCl values that are entrapped by insolubles.

(3) Slurry specific gravity measurement accuracy is of the order of plus or minus .5%. This is difficult to maintain.

CCP have overcome most of these problems, on their own, by employing techniques that resemble some features of the stream processor.

If the process stream is undersaturated and $MgCl_2$ is present the K^{40} analyser is not a workable instrument as is currently sold. However, one of the results of this study is that the mass-energy balancing technique will provide a means of using K^{40} probes, backed up with laboratory analyses, to obtain complete on-stream analysis, even if the stream is undersaturated and $MgCl_2$ is present in significant quantities. The methodology is particularly applicable to energy intensive circuits.

The following is a list of requirements for a crystallizer circuit:

(1) K^{40} probes on the following four circuit points:
- New Material
- Feed to the first effect
- Mother liquor from the fourth effect
- Product slurry to the centrifuges

(2) Flow measurement on the six topologically basic streams.

(3) Temperature on essentially all process streams. This is not a difficult measurement. One potash mine monitors all their process streams on-line for temperature. In any case temperature measurement need not always be an on-line measurement because of low sensitivity and low drift.

(4) Laboratory monitoring of reclaim brine condition.

(5) Water metering and stream flow measurement wherever water is added in significant quantities.

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Flow measurement on reclaim brine is a particularly important measurement and one should recognize the lack of provisioning that exists in all potash crystallizer circuits.

The above list might seem a tall order, but there are ways of reducing the additional requirements for a typical operation. This involves the use of the B-prototype to perform an in depth study of the error sensitivities of each item on the list to determine the required sampling frequency in each case. In some cases, for the plant control objective in mind, particular sampling frequencies may fall within laboratory analysis turn-around times. In other cases sampling times and sensitivities may show that estimation techniques for the measurement suffice.

Mass-Energy Balancing and On-Line Control

The prototype of this study is best described as a unit process supervisory controller that is based upon a mass-energy balance. Using the stream processor, the prototype can perform calculations that would be employed by a unit operations adaptive controller. It is worthwhile to pause in order to clarify this terminology as it is useful here and essential to the discussion on the C-prototype.

The terminology is most familiar to chemical process engineers as it is based upon the following hierarchical concept used in chemical engineering textbooks:

	Example
Process	Potash Process
Unit Process	The Crystallizer Circuit
Unit Operation	A Crystallizer Effect
Process Element	The Zone of Crystallization

In the crystallizer example that was pursued in this study, the crystallizer unit process, as a subset of the potash process was studied at the unit operations level. The mass-energy balance was used to tie all of the crystallizer unit operations together by the construction of a topological framework. However, the fundamentals of all process elements were incorporated into the formalism insofar as their steady state behavior was concerned.

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Control engineers employ a hierarchy of concepts and terminology that is equally relevant to this discussion. This is listed as follows:

Optimization

Supervision

Adaptation

Regulation

Monitoring

Monitoring and regulation are words that describe process control by the use of feedback control loops. Monitoring implies a mechanism of human intervention whereas regulation implies some degree of automation.

Optimization and supervision are two categories of multi-variable control. Supervision describes the interrelation of process variables in the implementation of a level of control that goes beyond the independence of the single control loop. A simple example of supervision is the adjustment of reagent setpoints based upon the level of mill feed at an earlier time when a mill feed disturbance was known to have occurred. Optimization is supervisory control based upon an objective function which may or may not be based upon economic variables. In cases where there are no economic variables the objective function contains elements that relate to the process economics or important process measures that ultimately influence process economics (for example recovery, grade, production or energy consumption.) An optimization that falls short of describing overall economics is called a sub-optimization.

In practice all mineral industry applications of optimal control involve some form of sub-optimization. A fundamental sub-optimization in complex multi-variable processes such as a crystallizer, is the maximization of the utility of the process instrumentation. This underlies the determination of the state of the process which is the goal of mass-energy balancing. However, the pursuit of this goal results in solutions to other related sub-problems such as the control of saturation in the crystallizer.

An adaptive control system is one containing elements of all the other control levels described thus far. This type of control depends to a high degree on artificial intelligence to identify the state of the process and to improve the quality of regulation. Typically, adaptive controllers are a combination of supervisory and regulatory controls with the additional capability of determining the state of the process so that correct setpoints or targets for process operation can be implemented.

Adaptive controllers fall into two categories, statistical and deterministic.

Statistical Adaptive Control

A **statistical adaptive controller** regards a process as a black box by assuming a control model that contains empirical parameters. An example of a black box model assumed by adaptive controllers is the second order plus dead-time model:

$$G_p(s) = K_p \exp(-t_d s)/((t_1 s + 1)(t_2 s + 1)) \quad \ldots\ldots\ldots (28)$$

which provides a description for a hypothetical process consisting of two holding tanks and inter-connecting pipelines between a sensor and a control valve. This hardware analogy describes the essential dynamic features of a general process subject to simple regulation. The model gives the Laplace transform of the process transfer function $G_p(s)$. K_p is the process gain (units conversion between valve control signal and process measurement), t_1 and t_2 are the retention times of the tanks and t_d is the transport lag of the piping. This model is the basis of most of the control analysis used since the invention of the pneumatic controller. It compliments the classical controller design which, in the time domain, has the following form:

$$m(t) = K(e + (1/T_I) \int e\,dt + T_D\, de/dt) \quad \ldots\ldots\ldots\ldots (29)$$

(29) is the so-called **PID** or Three-Mode algorithm for regulatory control which determines the control valve position m(t) as a function of time,t, by the summation of a term which is Proportional to the control deviation, a term which is proportional to the deviation time Integral and one that is proportional to the deviation time Derivative. The formula contains three parameters; the proportional gain K the integral time T_I and the derivative time T_D.

Much of the process control literature over the past 25 years has contained attempts to specify a schema for the determination of these tuning parameters by first identifying the current values of the parameters in equation (28) and then deriving the appropriate controller settings (tuning parameters) for equation (29). The failure to achieve this goal has it's roots in the low fidelity of equation (28) as a description of process dynamics and the unsuitability of equation (29) as a controller design.

As a result of experience in the field of Direct Digital Control(DDC) statistical adaptive controllers are being marketed that have been demonstrated on process plants in the aerospace, petroleum and the paper industries.

The approach involves the complete abandonment of the PID algorithm as the controller mechanism with the adoption of the generalized DDC algorithm:

$$m_t = \sum_k A_k e_{t-k} + \sum_k B_k m_{t-k} \quad \ldots\ldots\ldots\ldots\ldots\ldots (30)$$

which features a general dependence upon the last N deviations and valve settings. (30) can be reduced to almost any DDC algorithm that is currently in use including the usual implementation of equation (29).

Modern process controllers are not continuous as were earlier pneumatic and electronic controllers. They operate at time intervals which are commensurate with the process of sampling. Consequently, they are referred to as sampled data controllers. In equation (30) evidence of this follows from the observation that the valve position function is evaluated only at times:

$$t, t-1, t-2, \ldots\ldots, t-N$$

The statistical adaptive controller, NOVATUNE is based upon equation (30) and an undisclosed model for the process transfer function. The identification procedure is also proprietary but is thought to follow one of the methods developed by Daniel Graupe(4) in his text on process identification. The secrecy surrounding the ASEA methodology, in some ways is a deterrent to it's use. Nevertheless, the results of the use of the device for difficult problems in process regulation are quite spectacular.

Examples of such problems at the regulatory level in potash plants are:

(1) Saturation control on the discharge of crystallizer dissolvers.

(2) Level and density control in the crystallizer effect.

(3) Temperature control in dryer-cooler combinations.

(4) Density control in heavy media circuits.

Although, some of the current industry problems are attributable to sensing and actuation difficulties, some are attributable to a need for design improvements because the process design lacks controllability. Lack of controllability stems from mechanical inadequacies or originates with load or servo (operational) disturbances. Adaptive control can be useful in overcoming these problems.

Deterministic Adaptive Control

The present study is intended to cast some light of the fundamentals of the physical process. Consequently, the model so developed is described as deterministic. A deterministic adaptive controller identifies parameters in a deterministic model as part of the control action. Two applications have been identified in the control of potash processes. They are:

(1) Crystallizer interstage saturation control.

(2) Crystal nucleation and crystal size distribution

control.

The former application has been dealt with in the earlier discussion. It is noteworthy that the stream processor is a deterministic adaptive controller if implemented as an on-line instrument.

The latter application is beyond the scope of the B-prototype, but entirely within the scope of the C-prototype and, therefore, is relevant to the current discussion.

Randolf (10), pp 18-26, has outlined a possible control algorithm for particle size control in a crystallizer unit operation. In the previous study it was shown that particle size analyzers measure the moments of the particle size distribution (PSD). It can be demonstrated that the fundamental relations verified by Randolf's work provide a framework for the construction of an adaptive control algorithm where the parameters of the growth model can be determined from measurements of the PSD moments provided by the particle size analyzer. Such an algorithm requires supervision from a mass-energy balance as the measurement requirements of this adaptive control procedure would exceed that available from installed instrumentation.

Process Identification and the B-Prototype

The previous discussion dealt with on-line adaptive control. In it's application to process control the B-prototype requires constant tuning in terms of the process and physical parameters that are employed in the model.

Although the study endeavored to estimate these parameters, the major emphasis was placed upon the procedure and it's application. A study conclusion is that future parameter refinement will be required. The following is an incomplete list of most of the parameters that are contained in the mass-energy balancing procedure:

(1) Mineral Characteristics
- specific gravities
- insol composition
- specific enthalpies
- temperature coefficients related to the above

(2) Brine Characteristics
- solubility, specific enthalpy and specific gravity coefficients
- heats of solution
- vapor pressure factors
- seasonal factors for reclaim brine

(3) Unit Process Parameters
- heat exchange coefficients
- fouling parameters

. deportment parameters

Some of these parameters can be refined by model regression which is conducted as a by-product of the use of the system. This requires a sensitivity analysis of intermediate calculations to the above parameters. For example, the sensitivity of solubility parameters varies from stream to stream in a crystallizer circuit. Whenever, a mass energy balance shows a high degree of approach to steady state new information becomes available for certain streams of the process and can be used for model validation or parameter updating. Techniques to perform this analysis are outline in Graupe (4).

Circuits Other than a Crystallizer

The foregoing development is required for the evaporator, crystallizer, dryer and cooler circuits of a potash plant. In other cases this mass-energy procedure is overkill because the essential problem may only a need for mass-balancing. The previous discussion emphasized the crystallizer problem because it is a worst case for control in many ways. This does not mean that the control problems in other areas are easy. Indeed, the problems of grinding, compaction, heavy media separation and flotation are as perplexing in potash as they are in other mineral industry applications. The previous section dealing with on-line control is very pertinent.

The study has caused a reappraisal of such secondary areas from the point of view of the C-prototype. However, one must again be reminded that the supervisory level of control in these cases is directed by a mass-balance.

Two mass-balancing systems, MATBAL(7) and BILMAT(1) are available for mineral circuits, both developed by the SPOC program (Simulated Processing of Ore and Coal). During the study both of these systems were reviewed with regard to their use in potash circuit.

The BILMAT System

BILMAT (Bilan de Materiel) was developed at Laval University under the SPOC program and resembles the mass-energy balancing system of this study in several ways. In addition, it provides the capability for analyzing slurry streams and dry solids streams in terms of screen analysis. However, the system is very general and somewhat too sophisticated for most circuits. Moreover, it is very much tied to the use of water as a carrier of insoluble materials. The incorporation of potash solubility would involve a massive rewrite of the program. Furthermore the system uses the Powell algorithm(9) which would break down due to dimensionality if the application were a deslime circuit, a heavy media circuit or a flotation section of a potash plant which are likely targets for mass-balancing studies.

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MATBAL or MATBAL3

MATBAL3 is the most recent version of a system developed by Laquitton and is ideal for solving mass-balancing problems in water carrier circuits, even if the number of nodes and streams is quite high. The output of the system is a coherent mass-balance and a measurement oriented sensitivity analysis. The system assumes a linearized deportment and works best for overdetermined measurement sets. The limitation with regard to potash circuits is that it will not handle the solubility constraints. However, the code is concise and the system could be modified to include the stream processor. Kilborn plans to do this for flowsheet design purposes.

MATBAL3 Modification for the Mass-Balancing of Potash Circuits

The stream processor assumes measurement sets of the form:

$$x_{NT},\ x_{KT},\ x_{MT},\ x_{I},\ R,\ T$$

Although R is a questionable measurement in a crystallizer circuit, such is not the case on most wet milling streams due to the higher percent solids and the consequently higher information content in the s.g. measurement. This is related to the difficulty in measuring the more dominant insol fraction, necessitating the additional information contained in the R value. MATBAL also has a metallurgical accounting orientation that makes it suitable for performing brine corrections.

The modification described below has been applied by iterating MATBAL3 and the stream processor on simple cases to test the feasibility of the following procedure:

(1) Use the stream processor to transform laboratory measurement sets into stream measurement sets to give a first approximation to the solids/solution split on each stream.

(2) Upon completion of an appropriate number of MATBAL iterations the stream processor is used to correct the solution in order to correct drift from saturation. Undersaturation effects can be accommodated if necessary.

(3) The stream processor is used to clean up the final solution. This is needed only for cosmetic reasons; since this final step should be a very small move.

A properly designed and programmed system would incorporate solids and brine models and would perform an energy deportment on the circuit.

DESCRIPTION OF THE PROTOTYPE

Thus far in the report the following aspects of the mass-energy problem have been covered:

- The General Formulation
- The Crystallizer Application
- Implications for On-Line Control
- The General Potash Application

Included under these topics were considerations of solution chemistry, measurement, process identification, regulation and advanced control.

The following major section deals with only the B-prototype in terms of the following subjects:

- Specifics of Formulation
- Mathematical Programming
- Microprocessor Configuration
- System Software
- Application Programs

Due to the heavy detail of this specification section it is divided into two parts. The second section which contains most of the computer systems detail can be skipped on first reading, but it recommended for later readings of the report. The first section is a summary and it contains a slight re-ordering of the above list. This reordering is possible because of the content of previous sections.

Summary Description of the B-Prototype

The main box of the B-prototype is an IBM/XT compatible Professional Computer (PC). The reason for this choice is the wide range of scientific and engineering technology that is available through the IBM approach and the fact that an IBM mainframe was used in the previous study. The COMPAQ computer uses the IBM software and is portable which was valuable to the study.

However, the product required modification but contained within it's design provisions for expansion and modification that were sufficient for the requirements of the prototype.

Hardware Modifications

All three expansion slots in the COMPAQ/PLUS micro were used. The first was used for direct access storage, video controls and other more or less standard features are found on an IBM/XT.

The second slot houses a circuit board containing sufficient RAM (Random Access Memory) to raise the system to maximum memory and to provide a RAM disk. This enabled the system to house the full procedure in RAM and permitted high performance in the editing,

compilation and linkage of the many program modules that make up the procedure.

The third slot houses a communications microprocessor that allows communication with mainframe computers and process instrumentation via telemetry. Mainframe communication was useful for recovery of the library from the previous study and execution of the main procedure (COMEBAL) with control from the prototype.

The mother board was modified by the implantation of an INTEL 8087 microprocessor chip on a vacant slot created by the manufacturer. This procedure, now routine, requires a carefully controlled implant of the 40 pin chip plus heat insulation. The main microprocessor chip, the INTEL 8088, was replaced with another that was chosen to match the 8087. The 8087 performs mathematical operations at speeds of 30 to 100 times the speed normally attainable with just an 8088. The final mother board changes used INTEL 8086 technology for efficient program linkage in the software development phase.

Further modifications involved RF filtering on the power supply, surge protection and replacement of the box fan and filter.

The final result of all modifications is a microcomputer package that approaches mainframe speeds for calculations of the type encountered in mass-energy balancing.

Software

Modelling and process control in the Canadian Mineral Industry has encouraged the use of FORTRAN as a procedural language for model building. It is the language of the SPOC program and has had widespread usage in the scientific community since the early 1960s. It's shortcomings did not limit this study because of the benefits of widespread usage.

The FORTRAN that is supplied by IBM for use on their PC was found to be totally inadequate for the purposes of the study. There are severe limitations on the size of program modules and data arrays. These limitations are so severe that it would not be possible to store a procedure as large as COMEBAL.

The FORTRAN chosen was suggested by a Toronto firm that specializes in the building of special purpose microprocessors. It is sold under license by Microsoft Inc. of Belleview WA under the designation MS-FORTRAN Version 3.20. This software provides support for the 8087 microprocessor and is the only effective means of obtaining full utilization of this processor. This FORTRAN overcomes the memory limitations mentioned above but the first installation required a fix before this problem was resolved.

An independent systems developer provided a means for accelerated processing of several of the matrix structures that were

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encountered in the study. As a result, the following arithmetic, common to the ME procedure was speeded up considerably.

$$D_j^b = (m_c^{-1}) m_a D_j^a$$

This product is sold under the name MATRIXPAC V 3.1 by Microware, Inc. of Kingston, MA.

Program Development

One of the disadvantages of microcomputing is the slowness of the program preparation cycle which consists of:

(1) Program entry and editing

(2) Compilation

(3) Linkage editing

(4) Debugging

During the study about 95% of the elapsed computer time was confined to items (1), (2) and (3). 3% of the elapsed time was debugging and only 2% was spent operating the prototype for the industrial demonstration. The total amount of computer hours spent at a terminal was dramatically reduced by prototype features such as the RAM disk and the 8086 facilities within the Microsoft FORTRAN. This is worth underlining for the benefit of anyone undertaking prototype systems development. It is extremely important to pay as much attention to program development efficiency as it is to maximize the speed of the end product.

Application Considerations

Prototype feasibility was as much or more dependent on improvements in mathematical procedure as it was dependent on hardware and software innovation. It was clear at the outset that the problem had to be segmented in a hierarchy that was much more efficient than the one employed in the previous study. That hierarchy consisted of the following:

(1) A solids balance

(2) An analysis balance

(3) A water balance

The water balance is sub-optimal to the analysis balance which is in turn sub-optimal with respect to the solids balance. There is nothing fundamentally wrong with this approach since this mathematical structure patterns the dominant mathematical terms by analogy to the dominant physical terms in the process. The weakness in the procedure, apart from the handling of the solubility constraints, was the treatment of the enthalpy balance. In

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the previous study, the enthalpy constraint was part of the analysis balance. The argument that the stream enthalpy was highly dependent upon the solids/solution split because of the dominant heat of solution terms turned out to be incorrect. The nodal enthalpy imbalance is the main mathematical feature that must be corrected in the iterative computational procedure. This became evident when the NLP solution methodology was examined in depth. Consequently, the determinant of the solution is more the pulp flow vector on each stream than the solids/solution split. Therefore, a more correct hierarchy would be:

(1) A solids-enthalpy balance

(2) An analysis balance

(3) A water-enthalpy balance

(4) A temperature balance

Hierarchical minimization is heuristic by nature as there are no rigorous guidelines for specifying a procedure with optimal convergence. Therefore, trial and error is inevitably required in determining an efficient hierarchy.

The revised hierarchy is displayed as Figure VI. In this procedure the enthalpy constraint is satisfied within the water balancing problem, the solids balancing problem, and the temperature balancing problem.

Solubility constraints are imposed by preprocessing stream measurements on streams with composition measurements and extrapolation using equation (16) followed by preprocessing on unmeasured streams. These preprocessing steps provide the values a_{mj} that are contained in the J_3 objective function for the analysis balance. The statistics s_{mj} appropriate to these pseudo-measurements are unknown, but are of the order of magnitude of:

$$s_{1j}^2 = s_{2j}^2 = s_{NT}^2/2 \quad \text{etc.}$$

The water balance of the previous study is useful in providing a starting solution to the whole process. The analysis balance procedure ignores the enthalpy constraint but respects all aspects of consistency.

In the detailed section, the solids-enthalpy and water-enthalpy problems are shown to be non-linear programs having dimensions 6 and 14 respectively. Iteration of these problems with the analysis balance is pursued until the nodal enthalpy balance is less than a maximum amount. This amount, based upon an estimate of heat loss effects in the circuit, is the primary convergence parameter of the overall procedure. The value chosen for the study was somewhat arbitrary. In a more concerted study effort,

where a specific operating betterment is sought, considerable attention should be given to the identification of this parameter.

In the final step of the hierarchical procedure all streams are post-processed to respect the solubility constraint. This adjustment is mainly cosmetic.

Detailed Description of the B-Prototype

The following description is of a decomposition of the mathematical program defined by equations (10), (11) and (15) which define the general problem. The reader is urged to review this portion of the text before proceeding further.

The Water Balancing Problem (J_{12}^{a})

The water balance is solved in two ways:

(1) The First Approximation Balance

(2) The Water Mass-Enthalpy Balance

The first approximation balance is a quadratic program which is described in the first study report. It is based upon the water balance used in the BILMAT system. Measurements included in the objective function are:

(1) Pulp flow $\underline{D}_j^{p}$

(2) Water flow $\underline{D}_j^{w}$

(3) Dilution y_j

The constraint function is:

$$m_1 D_j^{w} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (31)$$

and the objective function is:

$$J_{12}^{a} = \sum_j ((D_j^{p} - \underline{D}_j^{p})/s_j^{p})^2 + \sum_j ((D_j^{w} - \underline{D}_j^{w})/s_j^{w})^2 + \sum_j ((y_j - \underline{y}_j)/s_j^{y})^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

The procedure provides an estimate of D_j as well as D_j^{w}. This is somewhat fortuitous for potash crystallizer circuits because measurements of the feed to the dust mix tank can only be obtained with great difficulty because of the variability of the material at the various collection points (dust collectors, effluent flotation etc.)

This first approximation procedure begins with an estimate of the solids balance on the basic streams. Consequently, at the end of the procedure a first approximation to the pulp flow vector D_j^{p} is available, which serves to linearize the constraints of the other balance procedures.

The Analysis Balance

The objective function is this case is:

$$J_3 = \sum_{mj} ((x_{mj} - a_{mj})/s_{mj})^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

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where a_{mj} are determined by applying the stream procedure to the set of all streams. This is done directly for measured streams, but only after extrapolation for other streams. Extrapolation is the application of the matrix transformation:

$$a_{Tmj}D_j^{cp} = -(m_c^{-1})m_a a_{Tmj}D_j^{ap} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(34)$$

which yields the values a_{Tmj} for all unmeasured streams in the circuit.

The values s_{mj} follow the statistics of measurement on measured streams and default to larger values on streams that are not measured.

The constraints of the analysis balance are as follows:

$$m_1 D^p (x_k + x_{k+3}) = 0$$

$$x_{mk} = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(35)$$

The J_3 problem is a quadratic program and although it's dimension is large, the solution is one step by the method of Lagrangian multipliers.

The Solids-Enthalpy Balance

The objective function is the same as the water balance problem. However, the independent variable is the basic solids vector which has six elements in the case of a crystallizer. Moreover, the objective function is no longer a pure quadratic because of the dilution term. By restricting direct variation to the basic vector and imposing indirect variation through the relationship:

$$D_j^c = -(m_c^{-1})m_a D_j^a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(36)$$

mass conservation is maintained at each step of this sub-procedure. The explicit constraint is conservation of enthalpy through variations in D^p:

$$m_1 D^p H = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(37)$$

which is linearized by the previous procedures that define a_m and D^p.

Dimensionality is low for this non-linear program but partial differentiation is complex. The complexity originates from the need to apply the chain rule for partial differentiation to terms in the objective and constraint functions that involve non-basic variables.

The Water-Enthalpy Balance(J_{12}^b)

The objective function is the same as the first approximation water balance. However, the constraint function is equation (37). The problem is a non-linear program of dimension $n_p - n_q = 14$ for

the crystallizer problem. By using the same search technique as in the solids-enthalpy balance the relation:

$$m_1 D^W = 0$$

is automatically satisfied at each step of the sub-procedure.

Non-linear programming resulted in poor convergence. This was overcome by constructing a quadratic program which was solved by the method of Lagrangian multipliers. It was possible to construct linearized constraints that would satisfy energy balance on each circuit node.

The Temperature Balance(J_4)

Enthalpy constraints are of the form:

$$(h_B + h_C) D^P = 0$$

where h_B is an enthalpy matrix over the set of basic water streams and h_C is an enthalpy matrix over non-basic streams; for all process units other than heat exchangers. Each of these enthalpy matricies can be approximated by a constant matrix plus another matrix that is proportional to a temperature difference vector. The above matrix structure leads to a linearization which is of the form:

$$Cdt = d$$

which can be subject to the minimization:

$$(dt/st)^T (dt/st)$$

where T indicates transposition. The temperature problem is solved with three iterations of this procedure yielding balances that approximate thermodynamic equilibrium.

Computational Considerations

Computation on a digital computer is performed in two ways. The two types of arithmetic are called real and integer. Integer arithmetic deals with numbers that do not have a fractional part. Real arithmetic involves numbers that have an integer and a fractional part. For example, 2.71828 is a real number having an integer portion 2 and a fractional portion .71828.

In this application the bulk of the computation is real arithmetic. The prototype does this arithmetic by linking FORTRAN calls to the INTEL 8087 math coprocessor via the Microsoft meta-command $nofloatcalls. Consequently, executable code will not operate on most IBM/PCs unless the 8087 microprocessor is added to a vacant slot on the mother board.

The real arithmetic in this system is REAL*4 and the integer arithmetic is INTEGER*2. This enables crystallizer circuits to be solved on the 16 bit microprocessor by minimizing the storage requirement for the large matrix arrays and maximizes speed for smaller more common arrays. Matrix arithmetic is by direct linkage to the 8087 for certain frequently used operations on non-symmetric matricies. Large symmetric matricies are inverted by a special routine which indirectly links these matricies, in compressed storage mode, to the 8087. In this way there is a trade-off between hardware speed and software efficiency.

The REAL*4 restriction imposed by 16 bit technology is barely sufficient for this problem at practical dimensions. The problem is within the iterative procedure where, on occasion, a matrix may become nearly singular. This may happen as a result of round-off or truncation error. Consequently, it is necessary to check the pseudo-rank of the matrix, in order to identify the row and column that is generating this degeneracy and then modify the input data. This procedure is involved, and the overhead associated with it's implementation, could not always be afforded. Instead, checks were incorporated to signal the offending intermediate, and removing it manually by adjusting an appropriate entry to remove the degeneracy.

The need for this corrective action can only be eliminated by doubling the precision of the computation. This is possible with the current technology but there is a 40% loss in the speed of computation. This is not the only problem. The addressing of large matrix arrays in storage is seriously compromised by limitations on the maximum size that can be handled with double precision. A 16 bit address can handle 64k byte blocks of contiguous storage, at maximum. Therefore, doubling the word length of real numbers cuts the maximum circuit dimension in half.

The study identified another source of problem degeneracy. If the circuit balance under study is not formulated properly then degeneracy can occur, as is illustrated in the following example. The crystallizer circuits shown in Figures I and II show two effluent streams connecting each effect. In formulating the topological networks shown as Figures III and IV it is tempting to consider the underflows and overflows as distinct process streams. This would have created a degenerate J_ problem by unnecessarily reducing the degrees of freedom of the constraint set. The fact that such a formulation is wrong can be deduced from chemical thermodynamic principles. The pertinent principle is described under the phase rule for unit operations that are in thermodynamic equilibrium. In these situations the number of degrees of freedom are determined by treating all effluent streams having the same temperature as being a single stream. Measurement of composition downstream is the only means of resolving their differences.

Another problem with 16 bit technology is the enormous problem of addressing storage beyond the ordinal limit of 64k. This is

accomplished, in the INTEL technology, by the use of segment registers, which expand the addressing capability to 20 bits. However, this device is far from being effectively implemented at the present time. An enormous amount of effort was expended on resolving difficulties with the Microsoft linkage editor which cut heavily into the project. Conceptually, this FORTRAN is capable of linking modules of a size in excess of 256k. However, in practice this has been accomplished in only a few cases. The COMEBAL procedure, in effect, is a worst case. Particular difficulty was encountered with provisioning for real time events. Although not too critical for the B-prototype, these considerations are extremely important to later developments. Therefore, it was deemed necessary to explore this area in depth. The final conclusion was that 32 bit internal precision is needed in micro technology, even though it has been safely foregone with mini and maxi-computers. For the purpose of the B-prototype several Microsoft fixes were applied.

Another problem was the inordinate amount of time required by the stream procedure. This was circumvented by a heuristic procedure which was based upon the NLP convergence process. The NLP procedure guarantees a solution, but, nevertheless, it is inefficient relative to some heuristic which is bounded by the problem. There is always a more efficient procedure which will yield solutions to the process, within the constraints of application. It should yield solutions, at considerable economy, without the overhead of rigor. Such a heuristic was found and implemented as the FORTRAN procedure named PREP. It is viable only within the limitations of the potash process and would probably fail in other industrial mineral processes such as mono-potassium sulphate or sodium sulphate. However, computationally it has an enormous advantage.

Measurement Statistics

The mass-energy balance of this study is statistically coherent. This statistical concept relates to the use of the reciprocal of the measurement variance as a weighting factor in the degree of approach of the balance to measurement. Theoretically, this weighting guarantees maximum likelihood if the measurement statistics are gaussian.

The sensing statistics of measurable variables can be determined crudely in a potash process. However, this crudity is inconsequential because the procedure is dependent only upon relative, not absolute variance estimates.

Flow and Density Measurement

Flow is measured volumetrically by magnetic flow meters, orifice plates or positive displacement pumping or metering devices in a potash circuit. Unless the flow is water or brine of stable composition the measurement is of little intrinsic value. An on-line instrument is at best accurate to 1% of full range and is

easily capable of drift to 5% accuracy unless given systematic calibration.

A flow measurement in conjunction with a density measurement is of considerable greater value. However, density on most potash streams must be measured to three places of decimals to be useful. Nevertheless, when measured in conjunction with flow, density measurement has statistics complementary to flow. This follows because the true measurement objective is the determination of solids flow by the relation:

$$D_p = RF$$

The variance of a product follows the sum of the squares of the multiplicand variances. This provides the relation:

$$s_p^2 = s_f^2 + s_r^2$$

as an order of magnitude estimate of the pulp flow variance.

B-Prototype Specification

Hardware

COMPAQ/PLUS c/w 640k RAM

AST SIXPAC PLUS:
.disabled parallel port and game adapter
.lithium battery clock

HAYES SMARTMODEM:
.inboard 1200B

INTEL 8087 Math Coprocessor c/w Matched 8088

RBG Monitor

EPSOM RX/80 Matrix Printer

EIA-RS-232-C Adapter

Software

MS DOS 2.0 or later

MICROSOFT FORTRAN 3.20

MICROSOFT 8086 Linker 3.14

8087.LIB Floating Point Library

FORLIB-PLUS Library Extensions(Alpha Computer Service)

PEDIT(Satellite Software Systems) or Equivalent Text Editor

SMARTCOM II Communications Monitor(Hayes)

SUPERDRV RAM disk emulator(AST)

SUPERSPL LPTn Spooler(AST)

MARTRIXPAC 8087 Matrix Processing(Microware)

SSP Scientific Subroutine Package(Included in Deliverables)

The bold capital letters are sufficient for ordering purposes from vendors of micro-computer software and hardware.

The COMEBAL procedure, as presently configured, requires 450k of RAM storage for execution. Utility procedures use the remainder of the 640k recommended in this specification. These utilities enable efficient compilation, editing and housekeeping procedures for the effective utilization of COMEBAL.

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This suite of computer programs solves the mass-energy problem by the use of FORTRAN NAMED COMMON. With this approach there are a number of restrictions that apply. Moreover, there are implicit definitions that are extremely difficult to alter. Before attempting any changes the user should become thoroughly familiar with the data structures.

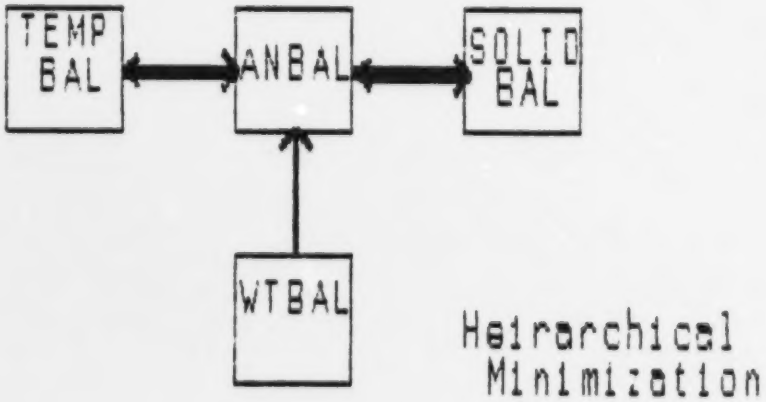
Environmental Requirements

This configuration approaches maximum for the system power supply. In order to protect the equipment it is necessary to use a surge protector to guard against noise spikes of short duration and high voltage that seem to be bothersome to microcomputers. Also the box fan on these small computers lacks filtration capabilities and can be easily upgraded by replacement with a more effective unit. Texas Instruments and other suppliers have inexpensive replacements.

Program Organization

The following Figure VI shows program organization:

FIGURE VI



A main procedure(COMEBAL), not shown above, controls the hierarchical minimization procedure. The entry point is the computation of the tons of dry solids and a water vector that will match the measurement set in the least squares sense. The procedure is similar to that employed by BILMAT. Successive water balances employ enthalpy constraints and are solved as an NLP or as a Lagrangian problem.

Having obtained this water balance an analysis balance is computed based upon the solids flow and water flows determined by

WTBAL. The solution so obtained will satisfy mass-balance and solubility because the analysis balance uses the stream processor on a stream-by-stream basis. The solution, however is not optimal from a solids deportment point of view; neither are the enthalpy constraints satisfied. Moreover, the water and solids vectors will be inconsistent with the analysis balance. A procedure to force this consistency is invoked at every step so that when revised water or solids vectors are obtained the procedure will finally close. Solids are balanced by an NLP which respects the enthalpy constraints. It will not satisfy them but it will cause enthalpy to be conserved at the current state of balance. Two procedures, the water balance and the temperature balance, when iterated with the above analysis balance procedure will converge to the solution of the overall problem provided that the sampling is reasonably coherent. Should this not be the case the procedure will break down, informing that a balance cannot be obtained with non-negative values for the measurements.

Most of the arithmetic in this system involves matrix algebra which is performed by matrix subroutines that are described in program documentation. In addition, a suite of programs will solve non-linear programs using the SUMT system which is described in (6). This procedure was adapted for use on microcomputers as part of this study.

Input to the system consists of the following:

(1) Network Data

(2) Temperature and Pressure Data

(3) Density and Flow Data

(4) Analysis Data

(5) A Starting Solution (Basic Solids Vector)

Output is illustrated by the case presented in the report.

An Industrial Demonstration

The following section contains an example case study which illustrates the industrial use of the B-prototype. The example is based upon a circuit which is similar to the CCP circuit, but involves sample information which is more typical of Cominco's operation in the early seventies. This combination was selected by Kilborn in the interests of providing an illustrative example without divulging confidential client information.

The circuit configuration of Figure I applies as does the topological numbering of Figure III. The entire procedure is available as a hands-on demo and is described in depth in the documentation deliverable.

In the example, the circuit is very close to thermodynamic equilibrium yet the measurement set is close to minimal. Thus it illustrates very well the situation of a reasonably well instrumented plant with effective operator regulation.

The view of the demo is a three screen display to the operator for each of the twelve unit operations of the circuit. The operator, under the assumption of a shift sampling program, has a means of studying the thermodynamics of the process over the period of his days work.

The following output shows what he would see for the hot thickener if he were to command the three screens for that unit operation at any time during the shift.

COMEBAL SCREEN DUMPS

A.

HOT THICKENER

STREAM	DP	NACL	KCL	MGCL2	H2O	INSOL
BAL FEED TO STG 1	-168.71	17.30	19.68	.05	62.98	-.01
MEAS	-171.64	17.31	19.82	.05	62.81	.00
STAT	.62	.10	.10	.01	.14	.32
BAL FEED TO HOT THKNR	172.09	18.05	19.69	.05	62.09	.12
MEAS	174.99	18.14	19.80	.05	61.91	.10
STAT	.62	.10	.10	.01	.14	1.00
BAL HOT THKNR U/F	-3.38	55.66	20.15	.02	17.68	6.49
MEAS	-3.02	55.15	19.53	.02	18.70	6.69
STAT	1.24	1.00	1.00	.01	1.42	3.16

Pause.
Please press <return> to continue.

B.

STREAM ANALYSIS

SLURRY COMPOSITION

	NACL	KCL	NACL	KCL
	SOLIDS		SOLUTION	
FEED TO STG 1	.00	.00	17.30	19.68
FEED TO HOT THKNR	.89	.00	17.16	19.69
HOT THKNR U/F	50.79	14.45	4.86	5.70

SOLUBILITY ANALYSIS

	NACL	KCL	NACL	KCL	TEMP	TEMP	TEMP
	SATURATION		BRINE		MEAS	BAL	STAT
FEED TO STG 1	17.46	20.39	17.29	19.68	87.80	89.24	1.10
FEED TO HOT THKNR	17.33	20.35	17.33	19.89	88.90	88.97	1.10
HOT THKNR U/F	17.20	20.17	17.20	20.17	87.80	87.80	1.10

Pause.
Please press <return> to continue.

C. HOT THICKENER
ENERGY ANALYSIS

	STREAM	TOTAL	RHO	RHO	RHO
	FLOW	ENTHALPY	ENTHALPY		SOLIDS	BRINE
FEED TO STG 1	168.71	.33E+06	-.55E+08	1.2426	2.6000	1.2426
FEED TO HOT THKNR	172.09	.32E+06	.55E+08	1.2476	2.1337	1.2423
HOT THKNR U/F	3.38	.14E+06	-.49E+06	1.7571	2.1012	1.2414
ENTHALPY IMBALANCE			.94E+04			

C>

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The previous page displays the three screens that are headed:

.HOT THICKENER

.STREAM ANALYSIS and SOLUBILITY ANALYSIS

.ENERGY ANALYSIS

The following is a description of how these screens are interpreted. The reader is encouraged to perform pocket calculator checks, as the information contained in these three "screen dumps" shows that the COMEBAL procedure has provided a solution to the general problem.

The HOT THICKENER Display

This screen shows the pulp flows into and out of the hot thickener. The convention is that a negative flow is an outflow and a positive flow is an inflow. Clearly, conservation of mass is preserved for this node of the circuit. This screen also shows that each stream species is individually conserved and that consistency(analyses add to 100%) is also maintained. The screen shows a comparison to measured values with the measurement statistics on an accompanying line; if that stream has been measured. An operator would keep an eye out for large deviations. Some of these he might interpret as instrument drift but generally he will be looking for approach to equilibrium.

The STREAM ANALYSIS Display

The STREAM ANALYSIS display shows a breakdown of the alkali components in terms of solids and solution. In this case, the operator would immediately note that the feed and the overflow are both probably undersaturated wrt KCl and all of the solids are reporting as underflow. This is a fairly normal condition and from the point of overflow and underflow this display is unremarkable. However, NaCl precipitation has occurred in the dissolvers and the operator would make a judgement as to whether the amount indicated is excessive. He would immediately turn his attention to the next portion of this display.

The solubility analysis is more revealing. It shows that the feed to the hot thickener is saturated wrt NaCl which it should be since solid NaCl is indicated from the previous portion of the display. However, he should note that saturation is at the equilibrium temperature and this is close to the measured value. The underflow is jointly saturated at the equilibrium temperature and this equals the measured value. The equilibrium temperature of the feed is slightly higher than the thickener ambient because of the 35psi steam addition just before the first effect. The operator might feel justified in increasing this steam addition to meet the equilibrium temperature of 1.27 degrees higher than the measured overflow temperature. The reader is now assured that

the COMEBAL procedure has respected the solubility constraints and that they are binding at the appropriate brine conditions.

The ENERGY ANALYSIS

This display repeats the mass flow rate from the balance for the pulp flow. The second value is the stream specific enthalpy (kJ/tonne) of the entire slurry. This number is mainly of academic interest to the operator but its appearance is a reminder of the relative heat values of the process streams. The reason why the feed and overflow streams have much higher specific enthalpies is that they contain larger brine components and the extra heat value represents heat of solution. To well within the accuracy of energy measurement the enthalpy is in balance and the operator's concern should shift to other points in the circuit. COMEBAL has obtained an enthalpy balance.

This display is of most interest to the plant metallurgist who is concerned with energy management. The final three items he would find most useful in improving the accuracy of his metallurgical calculations. The plant instrumentation engineer would find these values useful in checking the operation and calibration of density meters, particularly the important instrument on the underflow.

A Note on Computer Timing

The COMEBAL procedure for this case required 19 minutes for execution and the operator displays are available with a less than 1 second response time.

AN ADVANCED PROTOTYPE

The B-prototype is a powerful tool for analyzing potash circuits and it should be pressed into use for solving energy management and design problems. However, it falls short of serving as a process controller. Some of it's shortcomings are:

(1) The B-prototype is not an on-line device because it does not have software and hardware for data acquisition and final control.

(2) This prototype is not quite fast enough to keep pace with the real time demands of a circuit controller.

(3) The software component needs polishing up which will follow from application to more circuits.

(4) Stream analysis is the most critical measurement in the potash process and this is especially difficult in the case of high Mg circuits. The implication is that a total systems approach, covering the sampling system and the composition detectors, would be needed for engineering an advanced prototype.

An advanced C-prototype will contain the following additional features:

(1) Provision for key regulatory functions such as dissolver temperature control, feed saturation control, NaCl precipitation control etc. that will provide a means of correcting for out-of-kilter conditions detected by the mass-energy balancing procedure.

(2) Computation of key performance measures from on-line data acquisition is required. This would include tracking of heat exchanger heat transfer coefficients, wash down and purge schedules for the circuit.

Research on the Advanced Prototype

The scope of this study included investigation of the products and skills of Canadian developers and manufacturers of microcomputer products. This was done early in the study so that benefits would accrue to the B-prototype.

Initially, the registers of high technology companies were reviewed and telephone contacts were made with those that seemed appropriate. Through these contacts, product mailings and other information sources it was possible to identify about ten interesting prospects. A number of these proved most helpful and expressed considerable interest. An analysis of this canvass yielded four categories of companies:

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A. those specializing in process control and instrumentation across the process industries.

B. those that design and build specialized microsystems for specialized applications.

C. component and board manufacturers.

D. those manufacturing general purpose systems or major components for process control systems.

Category A

Category A companies can be sub-divided into:

. product line companies and

. systems integrators.

Product line companies such as Honeywell and Foxboro have little to offer in this case. These companies specialize in the marketing of large scale pre-developed systems. Not all of these companies are large, but most have one or two major products which are the mainstays of their business. Their personnel are tied to these products.

Systems integrators concentrate on solving process control problems through the use of systems engineering. They shy away from problems such as the C-prototype preferring work on the selection and procurement of systems from A-type companies.

Category B

This category consists of firms with technology skills in the design and development of specialized systems for relatively narrow application. Examples from the study were:

Topping Electronics, Scarborough, Ontario

Securistor Ltd., Montreal

Topping develops microsystems for traffic control and Securistor develops systems for security and fire protection. Both companies have strong expertise in microcomputers and offered helpful suggestions for both prototype systems. Their shortcoming is a lack of knowledge in this process application.

Category C

This includes chip manufacturers such as INTEL and Zylog. It also includes manufacturers of boards and sub-assemblies. The category B company draws upon these companies for component supply.

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One company, DY-4 Systems Inc. of Ottawa manufactures twenty different single boards some of which are of interest for C-prototype development. These boards make full use of 32 bit technology and provide a means of building systems which meet the C-prototype specifications.

Category D

These manufacturers produce assemblies for general purpose application in the fields of telecommunications and aerospace. From a technology point of view they are well staffed with all the skills of categories B,C and D. Their project preference, however, is to produce identical systems in quantity. Develcon Electronics of Saskatoon have expressed some interest in this project.

Throughout the research phase all companies displayed a certain amount of reluctance when presented with this problem. The reasons come forth gradually:

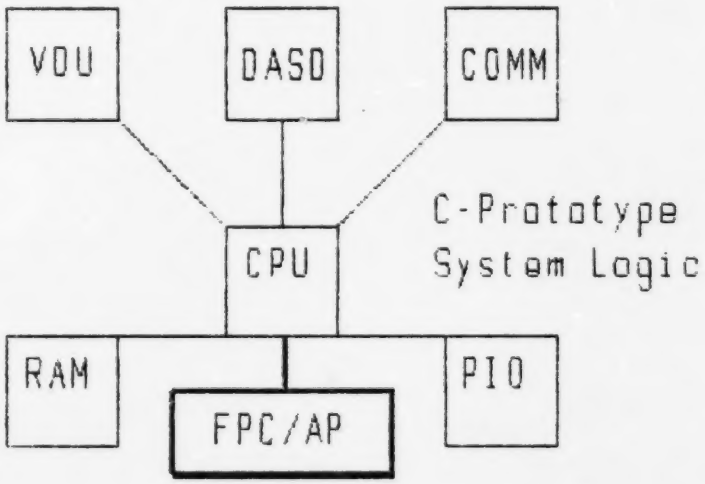
- these prototypes require large amounts of RAM
- a large amount of program code is required and its further development requires systems that will double as development vehicles as well as operational systems.
- there is wariness over the application in terms of understanding and appreciation.

However, it is felt that with the success of the B-prototype many of these concerns will be diminished.

A Specification for the C-Prototype

In the following specification all previously indicated requirements are met. In addition, about 100% overcapacity is allowed to provide unspecified features, the need for which will become more evident later on. The premium for this extra capacity will be about 20% of installed cost and the unit should install for $30,000.

The following is a diagram of the circuit boards that would be used in a C-prototype:



Eight single boards are shown which provide the following functions:

CPU	Central Processing Unit
RAM	Addressable Memory
FPC	Floating Point Coprocessor
AP	Array Processor
PIO	Process Input Output

VDU/PRT Video Display Printing Control Unit

COMM Communications Microprocessor

Bus Architecture

The essential glue for the system would be a mother board which would implement a data highway known as a bus. This would be a sixteen bit data path and would contain clocking and other control functions. A leading candidate is the VME architecture that is employed by DY-4 Systems.

Central Processing Unit

In order to meet speed and addressability requirements a processor chip such as the Motorola 68000 will be required. The 68000 is a 32 bit processor that is capable of working on a 16 bit bus. Moreover, this approach would be compatible with the UNIX operating system which is a leading software candidate for the operating system. UNIX was developed by the Bell Telephone Laboratory and appears to be the direction that even IBM is pursuing.

Addressable Memory

The 68000 has the ability to address 16 Megabytes of memory by using a 24 bit address. In the B-prototype there is a segmentation restriction which limits the maximum size of a data array or program module to 64k. The removal of this restriction is very important for ease of development. The minimum requirement for memory in the C-prototype is 2Megabytes.

Floating Point Coprocessor

In the B-prototype an INTEL 8087 math coprocessor was implanted on the mother board. It is unlikely that implantation would be followed in the case of the C-prototype. It is more likely that a floating point board will be required which may be integrated with the array processor.

Variable precision floating point is probably available, but could not be implemented if FORTRAN were maintained as the procedural language. If FORTRAN is retained, additional error diagnosis is a necessity at the chip level and at the software level in order to ease the burden of debugging procedural code.

Array Processor

This is an arithmetic unit that performs matrix operations such as MADD, MSUB ,MPRD and MINV for the addition, subtraction, multiplication and inversion of matricies. The COMEBAL procedure performs hundreds of matrix operations which includes rank determination and condition tests, in addition to the above list. Thus an array processor could be implemented on a high level and its performance impact would be dramatic.

Process Input/Output

The implementation of standardized instrumentation systems in potash plants has eliminated some compatibility problems. Analog and digital interfacing can now be considered compatible between recently installed instruments and process computers. However, there are still instruments from the previous era that require facilities on the process I/O board to assure connection. This includes isolation and variable range features. The process I/O should provide multiplexing and data conversion capabilities as well.

Video and Printer Adapters

In an engineering or process control application four features are needed in the graphics area:

- responsiveness
- resolution
- flexible color imaging
- ease of implimentation

In the B-prototype only responsiveness truly measured up to the application needs. There are shortcomings in all of the other three areas.

Resolution and color imaging could be improved by use of the Tesselator concept that was developed by the Swedish Manufacturer ASEA. However, there appears to be a lack of programming support for this method of imaging which does little to overcome the programming burden for ease of implimentation.

Communications

Although much progress has been made in this area, standards have been slow to change. This creates a compatibility problem because computer development and communications development tend to diverge at the leading edge. International agencies such as CCITT move slow relative to the advances that are being made in areas other than communications. Therefore, it is unlikely that much change will be made in the communications part of the C-prototype relative to that which is employed in the B-prototype.

Software

If the Motorola 68000 technology is employed then UNIX becomes the choice of operating system for the C-prototype because these are mutual enhancements. There are several features of the UNIX operating system that are so strong that they are suggested as requirements. Examples are:

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. multi-tasking that will allow program development and program maintenance to proceed concurrently with execution.

. device independence which will allow reconfiguration without program change.

. implimentation of full FORTRAN language facilities.

. support for the "C" programming language which will substitute for the use of ASSEMBLER language which is very difficult programming.

. systems integrity features that permit a greater capability for error detection, diagnosis and recovery for data, hardware and software problems.

During the course of the study IBM introduced the XENIX operating system (based on UNIX) as part of the IBM/AT product proving that there is not excessive overhead with UNIX.

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